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## ANALYSIS AND CORRELATION OF DATA OBTAINED BY SIX LABORATORIES ON FUEL-VAPOR LOSS FROM FUEL TANKS DURING SIMULATED FLIGHT

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

ANALYSIS AND CORRELATION OF DATA OBTAINED BY SIX LABORATORIES ON

FUEL-VAPOR LOSS FROM FUEL TANKS DURING SIMULATED FLIGHT

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## SUMMARY

Data on fuel-vapor loss from fuel tanks during simulated flight obtained by six laboratories were analyzed to show the effects of individual variables such as altitude, initial fuel temperature, rate of climb, booster-pump agitation, fuel depth, fuel-surface area, types of fuel, and vent-line pressure drop on fuel-vapor loss. From this analysis, the following conclusions were reached:

1. Fuel-vapor losses during flight were appreciable (3 percent) for flights to altitudes as low as 20,000 feet with an initial fuel temperature of 120° F. For a flight consisting of a climb to a 35,000-foot altitude with this altitude maintained for 8 hours and with the booster pump in operation; losses of 20 percent could be obtained with AN-F-28 fuel at an initial temperature of 120° F.

2. Most of the fuel-vapor loss occurred during the climb portion of the flight with relatively little loss during the remainder of the flight at constant altitude when no booster pump was used.

3. The fuel-vapor loss increased linearly with altitude beyond a critical altitude (the theoretical altitude at which fuel-vapor loss begins).

4. The critical altitude increased with decreased initial fuel temperature.

5. The fuel-vapor loss increased linearly with an increase in fuel temperature above approximately 80° F.

6. Booster-pump agitation markedly increased the fuel-vapor loss only during the constant-altitude portion of the flight.

7. Rate of climb to a given altitude had little or no effect on the fuel-vapor loss for rates of climb from 500 to 4000 feet per minute.

8. Fuel depth had no effect on fuel-vapor loss for depths varying from 1/3 foot to 2 feet. The losses due to foaming, surging, or boiling-over were not investigated.

9. Variations in fuel-surface area had little or no effect on fuel-vapor loss for surface areas varying from 0.034 square foot to 2.7 square feet.

10. Vent-line pressure differential increased with increased rate of climb and, at a constant rate of climb, built up rapidly soon after the critical altitude had been reached. When a constant rate of climb was maintained, the vent-line pressure differential tended to level off.

## INTRODUCTION

The fuel-vapor loss from an aircraft fuel tank during flight is controlled by flight variables and by fuel characteristics. Some of the basic concepts relating fuel characteristics to the problem of fuel-vapor loss have been investigated in connection with studies made on vapor-locking of fuel systems. The changes in fuel characteristics during flight, the effect of weathering, and the effect of air dissolved in the fuel on the vapor-locking tendencies of the fuel, as well as a method of reducing fuel-vapor loss by cooling the fuel before flight, have been discussed in several progress reports of the Coordinating Research Council. The factors affecting fuel-vapor loss discussed herein include altitude, initial fuel temperature, rate of climb, booster-pump agitation, fuel depth, fuel-surface area, types of fuel, and vent-line pressure drop.

Data covering the effect of these variables on fuel-vapor loss were obtained in 1943 and 1944 by six laboratories - Boeing Aircraft Company, Nash Engineering Company, Ohio State University Research Foundation, Pesco Products Company, Pratt & Whitney Aircraft, and Thompson Products, Inc. - for the Army Air Forces, Air Technical Service Command, and the Navy Department, Bureau of Aeronautics. At the request of the Army Air Forces, these data were analyzed at the NACA Cleveland laboratory during August and September of 1944.

## APPARATUS AND TEST PROCEDURE

The apparatus used by each of the six laboratories is listed in table I for comparison. In general, the apparatus consisted of a fuel tank subjected to altitude pressures by a vacuum pump, a means of measuring fuel loss during the test, and a means of controlling and measuring the fuel temperatures. The simulated-flight control usually consisted of a manually or automatically operated bleed valve in the line between the vacuum pump and the fuel tank for regulating the rate of climb and the altitude. The altitude pressure was measured by a manometer connected to the outer end of the vent line, by a manometer connected to the inside of the fuel tank, or both. The amount of fuel-vapor loss was found by measuring the change in fuel weight of a fuel tank mounted on a balance, by measuring the change in fuel volume with a calibrated glass window in the tank, or by condensing the escaping fuel vapor and taking volume measurements of the condensate.

A similar test procedure was followed by each of the six laboratories. The fuel was first heated to the desired initial fuel temperature and the fuel tank was then evacuated according to the desired flight path. Altitude-pressure and fuel-temperature readings were recorded at definite time intervals. A sample of the fuel was taken at the beginning and at the end of each test in order to measure Reid vapor pressures and to obtain A.S.T.M. distillation curves. The procedure followed and the simulated flights conducted by each of the laboratories are presented in table II.

## EVALUATION OF TEST PROCEDURE

### General Sources of Error

In order to evaluate properly the data presented, the several possible sources of error in the test procedure and the differences between the conditions that may occur during actual flight and those that may occur during simulated flight should be considered. These sources of error common to most of the test installations used to obtain the data in the six laboratories are discussed in the following paragraphs, not necessarily in the order of their relative importance because that order is not known.

1. Air leaks through the seams, the welds, and the fittings of the fuel tank are the most serious possible sources of error. A relatively small air leak near the bottom of the fuel tank would produce appreciable losses at the higher simulated altitudes and the losses would increase as the duration of the flight increased. In all tests, except those conducted by Nash, atmospheric pressure

was on the outside of the fuel tank and altitude pressure was on the inside. In most cases it was rather difficult, if not impossible, to be certain that no leaks were present.

2. In none of the tests, except those conducted by Nash and by Boeing (test setup No. 2), was any attempt made to control the temperature of the air surrounding the fuel tank. Although in all cases the fuel tank was insulated to some extent, any heat transfer from the fuel to the outside air would affect the test results. In the tests conducted by Nash, the surrounding-air temperature was maintained at 70° F; whereas, during the tests conducted by Boeing, the surrounding-air temperature was maintained equal to the fuel temperature.

3. In all of the tests except those conducted by Ohio State, the fuel temperature was measured at a single point in the fuel tank. In tests conducted with small quantities of fuel, such as those performed by Boeing on the preliminary test setup and on test setup No. 2 where 2 liters of fuel were used, it is entirely possible that the average fuel temperature was measured. With the larger quantities of fuel (5 to 30 gal) used by the other laboratories, it is highly improbable that the average temperature of the fuel throughout the tank at the start of the test could be measured at a single point unless the fuel was agitated for a long period of time. In the tests conducted by Ohio State, the thermocouples were located 6, 12, 18, 24, and 30 inches from the bottom of the tank. Thus an accurate check on the fuel temperature throughout the full depth of the tank was possible.

4. The effect on fuel-vapor loss of the amount of air dissolved in the gasoline was not investigated by any of the laboratories. This variable may have introduced some error in the reported test results but its magnitude cannot be estimated because the effect of dissolved air on fuel-vapor loss is not known.

5. Airplane altitude is usually considered to be the pressure altitude outside the airplane, which is the same as the pressure altitude outside the fuel-tank vent line. In the simulated flights conducted by most of the laboratories, the pressure altitude at the end of the vent line was controlled. In the tests conducted by Boeing and by Pratt & Whitney, however, the measured altitude was the pressure altitude existing within the fuel tank and therefore should differ from that measured by the other laboratories by the difference between the pressure within the fuel tank and the pressure at the end of the vent line.

Individual Sources of Error

The individual sources of error and the differences between actual-flight conditions and simulated-flight conditions for the test procedures of each of the six laboratories are as follows:

Boeing Aircraft Company. - Three test installations, referred to as "preliminary setup," "test setup No. 1," and "test setup No. 2," were used in the test conducted by Boeing. The test results obtained with test setup No. 2 were considered by Boeing to be the most reliable and the greatest emphasis was placed on these results.

In the fuel-tempering process in the preliminary setup and setup No. 2, the fuel was electrically heated. During this heating process, localized boiling might possibly have taken place and caused some fuel loss or weathering prior to the simulated flight. The Boeing report does not state whether the system was closed to the atmosphere during the tempering process nor whether attempts were made to measure any fuel loss occurring during this process.

The Boeing report does not state whether the weighing scale used in the preliminary setup and setup No. 2 was calibrated. With the vent and the manometer line connected directly to the flask, an incorrect weight measurement could possibly have been obtained.

Nash Engineering Company. - In the tests conducted by Nash, the fuel was brought to the desired temperature by circulating it through an external heat exchanger by a booster pump. The Nash report does not state whether the vent to the atmosphere was closed during this tempering process or whether an attempt was made to measure the loss, if any, during this period.

All fuel measurements were made on a volume basis and had to be corrected to present the data in terms of weight loss of fuel. Involved in the conversion are compensations for the temperature and for the specific gravity of the remaining fuel. The method used of determining the variation of specific gravity with percentage loss is not stated.

No fuel-loss measurements were made during the climb period. The fuel loss was calculated only at 10 minutes after the end of the climb and at the end of the test, although data were taken at definite time intervals throughout the constant-altitude portion of the simulated flight.

Ohio State University Research Foundation. - The data presented by Ohio State show that the Reid vapor pressure of the gasoline measured before the start of the tests varied from 5.32 to 6.42 pounds per square inch. Figure 1, obtained from test data, shows that a variation of initial Reid vapor pressure between these limits may cause a variation of as much as 8 percent in the fuel-vapor loss. (The initial Reid vapor pressure of test No. 2-120-B1 was 2.08 pounds per square inch. Inasmuch as this initial Reid vapor pressure was lower than the final Reid vapor pressure of this particular test, it was considered to be a typographical error.)

The Reid vapor pressure of the fuel at the start of the tests decreased with an increase in the initial fuel temperature. This decrease indicates that the fuel may have been weathered during the heating process. In some cases the gasoline was stirred in the fuel tank to equalize the fuel temperature within the tank but the method of stirring the gasoline is not stated. Stirring of the gasoline may weather the fuel and affect the fuel-vapor loss, especially if the tank is vented to the outside atmosphere during this process.

Pesco Products Company. - Very little information is presented in the Pesco report about the test procedure used. From the information obtained during a telephone conversation with Mr. R. B. Wallace, project engineer for these tests, it was concluded that some of the possible sources of error are as follows:

1. The scale used during the tests was not calibrated. With the vent, the manometer, the thermocouple, and the booster-pump lines connected directly to the fuel tank, it is possible that an incorrect weight measurement could have been obtained.

2. The fuel was heated by circulating it through the coils of an oil bath maintained at a temperature of approximately 150° F. Some localized boiling of the fuel may have occurred in the oil bath because the initial boiling point of the fuel is below 150° F (normally between 100° F and 120° F).

3. Some of the vapor formed during the tempering process by localized fuel boiling and agitation may have escaped through the vent line inasmuch as it was open during this period. The Pesco report does not state whether any measurements of possible fuel loss during this period were made. No check on this possible loss can be made because the initial fuel sample was removed before the fuel-tempering process.

4. The fuel temperature was measured by a single thermocouple located approximately $1\frac{1}{2}$ inches from the bottom center of the tank, which may not have measured the true average fuel temperature within the tank.

Pratt & Whitney Aircraft. - The fuel was heated to the desired initial temperature by steam coils. Inasmuch as the temperature of steam at or above atmospheric pressure is well above the initial boiling point of AN-F-28, grade 130 fuel, localized boiling around the heating coils could have occurred with possible resultant fuel loss before the beginning of the actual test.

The condensed-vapor method used for measureing the fuel-vapor loss is subject to some error. Unpublished data obtained at the NACA Cleveland laboratory indicate that fuel recovery by condensation (at extremely low temperatures) after vaporization seldom yields complete recovery. Between the time the fuel was lost and the time it was recovered, a time lag existed that was not accounted for in the data presented.

During the fuel-tempering process, the fuel was held at the desired initial temperature for 15 minutes before the start of simulated flight. The fuel booster pump was operated during this time for better temperature equalization. The Pratt & Whitney report does not state whether any fuel loss occurred during this period of fuel conditioning or whether any attempt was made to measure such loss.

All measurements were made on a volume basis and were corrected to present the data in weight loss of fuel. Involved in the conversion are compensations for the temperature and for the specific gravity of the recovered fuel. The variation of specific gravity with volume percentage loss was determined by measuring the specific gravity of the fuel distilled, using an A.S.T.M. distillation apparatus. The value of the results of this procedure is doubtful because the process of boiling the fuel to produce the vapors in an A.S.T.M. distillation apparatus may be vastly different from the process of loss through the decreased pressure of simulated flight. No evidence is presented to substantiate the supposition that the two processes produce identical fuel losses of identical composition.

Throughout the Pratt & Whitney report all curves are presented without the experimental-data points, although it was stated that readings were taken every 2 minutes during the test. The presence of data points would permit a more comprehensive analysis of the data. Some variation between tests is indicated, especially in one case, where, because the rates of climb in all tests were the same, the losses during the climb period for the three tests should agree but do not. For example, the fuel loss after a climb to 35,000 feet is 2.15 percent in one test and 3.2 percent in another (a possible difference of approximately 49 percent).

<u>Thompson Products, Inc.</u> - The data presented by Thompson Products show that the Reid vapor pressure of the gasoline measured before the start of the test varied from 6.1 to 6.7 pounds per square inch. Figure 1 shows that a variation of initial Reid vapor pressure between these limits may cause a variation of as much as 4.2 percent in the fuel-vapor loss.

Probably the most serious source of error in this series of tests is the variation of the temperature of the air surrounding the fuel tank (from 42° F to 79° F). The temperature of the air surrounding the fuel tank was consistently lower during the agitated runs than during the unagitated runs.

## RESULTS AND DISCUSSION

Although the apparatus and the test procedure used by each of the laboratories varied somewhat, the results obtained can be compared on the basis of the several variables studied. As many as possible of the data presented were used, although in some cases only one or two laboratories obtained data for a particular variable. The results obtained by the six laboratories were compared on the basis of the effects of the individual variables such as altitude, initial fuel temperature, rate of climb, fuel agitiation by means of a booster pump, fuel depth, fuel-surface area, types of fuel, and vent-line pressure drop on the fuel-vapor loss during simulated flight. When a comparison was made of the results obtained by each of the six laboratories for a particular variable, an attempt was made to compare them with the other conditions held constant.

### Simulated-Flight Time

All the laboratories usually measured the fuel-vapor loss during simulated flight as a function of simulated-flight time. (See fig. 2.) The curves of fuel-vapor loss plotted as a function of simulated-flight time have the same general form and show that the greater part of the fuel-vapor loss took place during the climb period, with relatively little loss during the remainder of the flight at constant altitude. It is believed that the rapid fuel boiling caused by the decrease in pressure above the fuel during the climb period ends shortly after the start of the constant-altitude portion of the simulated flight. The loss occurring thereafter could be due to normal evaporation into the surrounding atmosphere at the new altitude.

## Altitude

The effect of altitude on fuel-vapor loss is shown in figure 3, in which the fuel loss during the climb period has been plotted as a function of altitude with initial fuel temperatures of 60°, 80°, 90°, 100°, 110°, and 120° F. A representative average has been drawn for each temperature and these curves are presented in figure 4. In these curves the data obtained by Pesco varied so greatly from the average of the data obtained by the other laboratories that they were disregarded when the average curve was drawn. In figure 4 the curves for the various initial fuel temperatures follow the same general trend. Each curve shows a negligible loss up to an approximate critical altitude (the theoretical altitude at which fuel-vapor loss begins) from which point the fuel-vapor loss increases linearly with increased altitude. The small transition section preceding the linear portion of the curve may be caused by the presence of air either in solution within the fuel or above the fuel, which, upon being removed, carries with it some fuel vapor. The fact that the variation of fuel-vapor loss with altitude is a linear function is amply brought out in figure 5, in which data are plotted from a test conducted by Boeing to an altitude of 55,000 feet.

Inasmuch as the slopes of the linear portions of the curves of figures 4 and 5 are very nearly equal, the following equation based on the average slopes of these curves, neglecting the transition section where the loss is small, can be derived to approximate the variation of fuel-vapor loss with altitude during a climb:

$$L = \frac{Z - Z_c}{1.86} \tag{1}$$

where

$L$ fuel-vapor loss, percent

$Z$ altitude, in 1000 feet

$Z_c$ critical altitude, in 1000 feet

## Initial Fuel Temperature

The marked effect that initial fuel temperature has on fuel-vapor loss is shown in figure 4. Because the vapor pressure of the fuel increases with temperature, the critical altitude decreases with increased fuel temperature. The critical altitude can be obtained by extending the linear portion of the curve of fuel-vapor loss plotted against altitude to the point of zero loss. The critical altitudes thus obtained from figures 4 and 5 are plotted as a function of temperature in figure 6. This figure indicates that a linear relation exists between the initial fuel temperature and the critical altitude. This relation for the fuels used in these tests may be expressed by the equation

$$Z_c = 59.4 - 0.37\,T \tag{2}$$

where T is the initial fuel temperature in $^{\circ}$F.

Equation (2) may be combined with equation (1) to give a possible general equation for the fuels used in these tests relating the fuel-vapor loss during a climb to altitude with initial fuel temperatures between 60° F and 120° F:

$$L = \frac{Z + 0.37\,T - 59.4}{1.86} \tag{3}$$

It may be necessary to obtain additional data to establish completely equation (3) for future use.

The fuel-vapor loss at several periods during the test (10 min, 1 hr, and 8 hr after the end of the climb period) is plotted in figure 7, which shows that fuel-vapor loss tends to vary linearly with initial fuel temperatures above approximately 80° F after the end of the climb period as well as during the climb period.

## Rate of Climb

The effect of rate of climb to a given altitude on fuel-vapor loss is shown in figure 8. Although all the data presented were obtained by Boeing, the results indicate that the rate of climb to a given altitude had little or no effect on fuel-vapor loss with rates of climb varying from 500 to 2000 feet per minute. The Nash tests also indicated that no appreciable change in fuel-vapor loss occurred with a change in the rate of climb from 2000 to 4000 feet per minute. The data obtained by Boeing cannot be directly compared with those obtained by the other laboratories because the Boeing tests were conducted with an initial fuel temperature of 110° F, whereas the tests of the other laboratories were conducted with initial fuel temperatures of 120° F and 100° F. The two average fuel-vapor curves from figure 4 at initial fuel temperatures of 120° F and 100° F with rates of climb of 4000 feet per minute are also shown in figure 8. The curves obtained by Boeing fall very nearly midway between the other two curves with almost the same characteristics and slope, which seems to indicate that rate of climb has little or no effect on fuel-vapor loss, even up to a rate of climb of 4000 feet per minute. Increased rates of climb above 4000 feet per minute may cause increased fuel loss if surging and foaming are encountered.

## Booster-Pump Agitation

A series of curves showing fuel-vapor loss as a function of initial fuel temperature (fig. 9) similar to the series showing the effect of initial fuel temperature on fuel-vapor loss was obtained with the fuel agitated and circulated by a booster pump. This series of curves and the series obtained with the fuel unagitated are replotted in figure 10 for comparison. This figure indicates that the fuel-vapor loss both with and without agitation tends to be nearly equal at the end of the climb period. Figure 10 also indicates that, as the flight progresses at constant altitude, the loss with agitated fuel becomes increasingly greater than that with the unagitated fuel. During the climb period, the high rate of fuel loss resulting from the boiling of the fuel is accompanied by considerable agitation of the fuel. The action of the booster pump adds little to the agitation already present or to the fuel loss during the relatively short climb period. During the relatively long quiescent constant-altitude portion of the simulated flight, however, the additional loss due to booster-pump agitation is readily evident.

## Fuel Depth

Data obtained by three laboratories (Ohio State, Thompson, and Nash) on the effect of fuel depth on fuel-vapor loss at 10 minutes after the end of the climb to 35,000 feet with an initial fuel temperature of 120° F are presented in figure 11. This figure indicates that fuel depth has no effect on the fuel-vapor loss for fuel depths varying from 1/3 foot to 2 feet. The losses due to surging, foaming, or boiling-over when the fuel tank is filled close to capacity were not investigated.

## Fuel-Surface Area

Nash, the only laboratory reporting tests on the effect of fuel-surface area on fuel-vapor loss, conducted similar tests with two fuel tanks, one having a fuel-surface area of 1 square foot and the other a fuel-surface area of 2.7 square feet. Nash reports an average fuel-vapor loss of 16.7 percent (average of four tests) during a simulated flight with the smaller tank and 16.37 percent (average of three tests) with the larger tank for the same simulated flight. These results seem to indicate that the variation of surface area has a negligible effect on fuel-vapor loss.

Table I indicates that four of the other laboratories conducted tests in which the fuel-surface areas were nearly equal (approximately 2.7 sq ft); whereas Boeing (with test setup No. 2) conducted tests in which the fuel-surface area was extremely small (approximately 0.034 sq ft). The fuel-vapor-loss correlation obtained among the six laboratories in figures 3, 7, and 10 indicates that the surface area of the fuel has little, if any, effect on fuel-vapor loss. Insufficient data are presented for a more comprehensive analysis.

## Types of Fuel

Several fuels were used by the various laboratories in the tests conducted to determine the fuel-vapor loss during simulated flight. Boeing and Pratt & Whitney (and, although not stated, probably Thompson and Ohio State) used AN-F-28 fuel; Pesco used 87-octane and 65-octane fuel; and Nash used AN-VV-F-776, Amendment-3 fuel and AN-VV-F-781, Amendment-5 fuel. (See table I.)

As indicated in figure 2, the fuels used by Nash resulted in a slightly lower fuel-vapor loss than those used by Ohio State and Thompson. The loss under the same conditions for Pesco is not plotted in this curve because it was so large as to preclude the possibility of any cause except air leakage. (Loss at the end of the Pesco test for the same conditions as those shown in fig. 2 was 38.4 percent.) In figure 7 the fuel-vapor losses at several initial fuel temperatures for each of the laboratories, except Boeing, are compared and show no general trend. Insufficient evidence is presented for a comprehensive analysis.

## Pressure Drop in the Vent Line

The pressure drop in the fuel-tank vent lines is important because a pressure differential less than a specified maximum must be maintained across the wall of the fuel tank during flight to assure the self-sealing properties of the fuel tank when it is penetrated by gun fire.

Data obtained by three laboratories (Nash, Thompson, and Boeing) on the pressure drop in vent lines during simulated-flight tests under several flight conditions are presented in figures 12 and 13. Because of the variations in size and configuration of the vent lines used in the various tests, the results obtained from those laboratories cannot be compared; the results obtained by each laboratory, however, will be discussed individually.

Nash Engineering Company. - The vent line consisted of 10 feet of 1-inch-outside-diameter vent pipe and was wound in a large loop around the fuel tank within the altitude chamber. The pressure drop in the vent line was measured by a differential manometer connected between the inside of the fuel tank and a point near the end of the vent line.

The variation in vent-line pressure differentials during simulated flight for several initial fuel temperatures (shown in fig. 12(a)) is similar, with the initial pressure differential occurring at the initial point of appreciable fuel-vapor loss (probably close to the critical altitude). The pressure differential tends to reach a maximum within a relatively short time and then levels off for the remainder of the climb period. The leveling-off can be expected because the rate of fuel-vapor loss with altitude is constant during this period of the simulated flight and the pressure differential through the vent line is a function of the weight rate of flow through it.

Thompson Products, Inc. - The vent line used in the tests conducted by Thompson consisted of 10 feet of 1-inch-outside-diameter tubing containing three 90° bends and made up of seven sections in all, each connected by flexible couplings. The pressure drop in the vent line was recorded as the difference between the pressure in the fuel tank and that in the "altitude tank." The curves of pressure drop as a function of altitude (fig. 12(b)) are of the same general shape and start at approximately the same altitude as those shown in the Nash report (fig. 12(a)). The rapid increase in pressure drop over the pressure drop reported by Nash is possibly due to the increased resistance offered by the bends and couplings in the vent line.

Boeing Aircraft Company. - The curves presented in figure 13 were plotted from data obtained on test setup No. 1, in which the vent-pressure drop during simulated flight at several rates of climb was plotted as a function of altitude. The company report does not state how the pressure drop in the vent line was measured. It is therefore assumed that the pressure drop was measured as the difference between the pressure in the vacuum tank and that in the Erlenmeyer flask. From an inspection of the photograph of the test installation, the vent line appears to be about 3 feet long and to contain a 3/8-inch orifice connected by sections of 1-inch self-sealing hose to a gate valve mounted on the altitude tank. The curves show that the pressure drop in the vent tube at a given altitude increases with an increase in rate of climb. This condition is to be expected because the rate of fuel-vapor loss increases with increased rate of climb and the pressure differential across the vent line is a function of the weight rate of flow through the vent line. The drop in pressure differential with increase in altitude before the end of the climb period, however, was probably due to the fact that a constant rate of climb of 2000 and 4000 feet per minute could not be maintained.

General trends. - On the basis of the data presented from the Nash, Boeing, and Thompson laboratories, several general trends can be noted. The vent-line pressure differential: (1) increases with increased rate of climb; and (2) increases rapidly with increased altitude at the point at which appreciable fuel-vapor loss occurs and has a tendency to level off if a constant rate of climb is maintained.

## CONCLUSIONS

On the basis of a comparison of the data presented by six laboratories on the fuel-vapor loss from fuel tanks during simulated flight, the following conclusions have been reached:

1. Fuel-vapor losses during flight were appreciable (3 percent) for flights to altitudes as low as 20,000 feet with an initial fuel temperature of 120° F. For a flight consisting of a climb to a 35,000-foot altitude with this altitude maintained for 8 hours and with the booster pump in operation, losses of 20 percent could be obtained with AN-F-28 fuel at an initial temperature of 120° F.

2. Most of the fuel-vapor loss occurred during the climb portion of the flight with relatively little loss during the remainder of the flight at constant altitude when no booster pump was used.

3. The fuel-vapor loss increased linearly with altitude beyond a critical altitude.

4. The critical altitude increased with decreased initial fuel temperature.

5. The fuel-vapor loss increased linearly with an increase in fuel temperature above approximately 80° F.

6. Booster-pump agitation markedly increased the fuel-vapor loss during the constant-altitude portion of the flight only.

7. Rate of climb to a given altitude had little or no effect on the fuel-vapor loss for rates of climb from 500 to 4000 feet per minute.

8. Fuel depth had no effect on fuel-vapor loss for depths varying from 1/3 foot to 2 feet. The losses due to foaming, surging, or boiling-over were not investigated.

9. Variations in fuel-surface area had little or no effect on fuel-vapor loss for surface areas varying from 0.034 square foot to 2.7 square feet.

10. Vent-line pressure differential increased with increased rate of climb and, at a constant rate of climb, built up rapidly soon after the critical altitude had been reached. When a constant rate of climb was maintained, the vent-line pressure differential tended to level off.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 19, 1944.

TABLE I - APPARATUS USED IN FUEL-VAPOR-LOSS TESTS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

| Laboratory → | Boeing Aircraft Company | | | Nash Engineering Company | Ohio State University | Pesco Products Company | Pratt & Whitney Aircraft | Thompson Products, Inc. |
|---|---|---|---|---|---|---|---|---|
| Fuel → | AN-F-28, grade 100/130 | | | AN-VV-F-776, Amendment 3, grade 91<br>AN-VV-F-781, Amendment 5, grade 100 | Not stated | 87 octane<br>65 octane | AN-F-28, grade 130 | Not stated |
| Fuel-tank setup: | Preliminary setup | Test setup No. 1 | Test setup No. 2 | | | | | |
| Shape and material | Erlenmeyer flask | Glass cylinder | Erlenmeyer flask | Cylindrical steel tank | Cylindrical steel tank | Cylindrical steel tank | Cylindrical steel tank | Cylindrical steel tank |
| Dimensions or capacity | 2 liters | 10 gal | 2 liters | $13\frac{3}{8}$-in. I.D., 36 in. long and $22\frac{1}{4}$-in. I.D., 24 in. long | By approximation $22\frac{1}{2}$-in. I.D., 36 in. long | 2 ft in diameter, 3 ft high | Appears to be 55-gal drum | $19\frac{5}{8}$-in. I.D., $35\frac{5}{8}$ in. long |
| Insulation | None | None | Lagged with asbestos | Insulated with 3/8-in. sponge rubber | Insulated with 3/8-in. thickness of rubber | Insulated with $1\frac{1}{2}$-in. thickness of "Asbestocel" | Well insulated | Completely insulated with 3/8-in. thickness of cellular rubber |
| Vent line | 48 in. of 0.16-in. I.D. glass tube | 1-in. I.D. Neoprene hose with 3/8-in. orifice assembly | Neoprene tubing | 10 ft of 1-in. O.D. tubing | 10 ft of 1-in. aluminum tubing | 10 ft of 1-in. O.D., 0.049-in. wall dural tubing | | 10 ft of 1-in. I.D. tubing |
| Method of agitation | None | None | None | Nash booster pump | Pesco booster pump | Pesco booster pump | Thompson booster pump | Thompson booster pump |
| Method of simulating flight: | | | | | | | | |
| Vacuum pump | Vacuum pump | Vacuum pump | Vacuum pump | Fuel tank placed in altitude chamber | Steam-jet ejectors | Vacuum pump | Suction side of compressor | Vacuum pump |
| Pump control | Hand valve | Hand valve | Hand valve | Altitude controlled automatically | Hand valve | Hand valve | Hand valves | Hand valve |
| Method of measuring altitude | Mercury manometer | Mercury manometer | Mercury manometer | Pressure recorder | Mercury manometer and recording gage | Mercury manometer | Aircraft rate-of-climb indicator and altimeter | Mercury manometer |
| Location of altitude indication | Inside fuel tank | Inside fuel tank | Inside fuel tank | Inside vent line, 10 ft from fuel tank | Inside vent line, 10 ft from fuel tank | In surge tank, at end of vent line | Inside fuel tank | In surge tank, at end of vent line |
| Method of determining fuel-vaporization loss | Tank mounted on balance | Tank mounted on balance | Tank mounted on balance | Change in volume in fuel tank observed through glass windows in tank | Tank mounted on balance | Tank mounted on balance | Volume measurement of amount of fuel condensed by condenser operating at -80° F | Tank mounted on balance |
| Method of controlling fuel temperature: | | | | | | | | |
| System used | External heating of flask by electric heater | Circulating hot water (110-120° F) through copper coils in cylinder | External heating of flask by electric heater | External hot-water heat exchanger, water circulated by booster pump at 200 gal/hr | Circulating hot water (40° F to 200° F) through coils in fuel tank | Circulating fuel through coil immersed in oil bath at 150° F | Circulating steam through coils in fuel tank | Fuel circulated by pump through a hot-water heat exchanger at 1200 lb/hr, rate of heating adjusted to 1° F/min |
| Method of measuring | Thermometer at bottom of flask | Thermometer near bottom of cylinder | Thermometer at bottom of flask | Thermometer 6 in. from bottom of tank | Thermocouples spaced 6, 12, 18, 24, and 30 in. above bottom of tank | Single thermocouple $1\frac{1}{2}$ in. from bottom center of fuel tank | Thermocouples in bottom and center of tank | Thermocouples in tank and in inlet and outlet of heat exchanger |
| Ambient-air-temperature control | Heater used to maintain ambient-air temperature at fuel temperature | None | Heater used to maintain ambient-air temperature at fuel temperature | Altitude chamber temperature maintained at 70° F | None | None | None | None |
| Sample analysis: | | | | | | | | |
| A.S.T.M. distillation | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Reid vapor pressure | No | No | No | Yes | Yes | Yes | Yes | Yes |

TABLE II - PROCEDURES AND VARIABLES IN SIMULATED-FLIGHT FUEL-VAPOR-LOSS TESTS

| Laboratory → / Variable ↓ | Boeing Aircraft Company | | | Nash Engineering Company | Ohio State University | Pesco Products Company | Pratt & Whitney Aircraft | Thompson Products, Inc. |
|---|---|---|---|---|---|---|---|---|
| | Preliminary setup | Test setup No. 1 | Test setup No. 2 | | | | | |
| Fuel quantity | Approx. 2 liters | Approx. 5 gal | Approx. 2 liters | 1/3-, 2/3-, 1-, and 2-ft depths, 1- and 2.7-sq ft surface Approx. 2.6 to 20.5 gal | 1- and 2-ft depths, approx. 124 and 248 lb | 1- and 2-ft depths, approx. 135 and 270 lb | [a]10 to 30 gal | 1- and 2-ft depths, approx. 95 and 190 lb |
| Initial fuel temperature, °F | 110<br>111 | 107<br>110 | 60, 90, 100 110, and 120 | 60, 80, 100, and 120 | 60, 80, 100, and 120 | 60, 80, 100, and 120 | 80, 100 and 120 | 60, 80, 100, and 120 |
| Simulated flight rate of climb, ft/min | 1000 | 500, 1000, 2000, and 4000 | 250, 500, 1000, and 2000 | 2000 and 4000 | 4000 | 4000 | 1000 | 4000 |
| Altitude, ft | 40,000 | 40,000 | 40,000 | 15,000<br>25,000<br>35,000<br>50,000<br>65,000 | 35,000 | 35,000 | 25,000<br>30,000<br>35,000<br>40,000 | 35,000 |
| Duration of flight, hr | Climb only | Climb only | Climb only | 8 | 8 | 8 | 2 | 8 |
| Agitation | None | None | None | 1. None<br>2. With booster pump | 1. None<br>2. With booster pump | 1. None<br>2. With booster pump | 1. None<br>2. With booster pump | 1. None<br>2. With booster pump |

[a]"Depending upon amount of loss anticipated"

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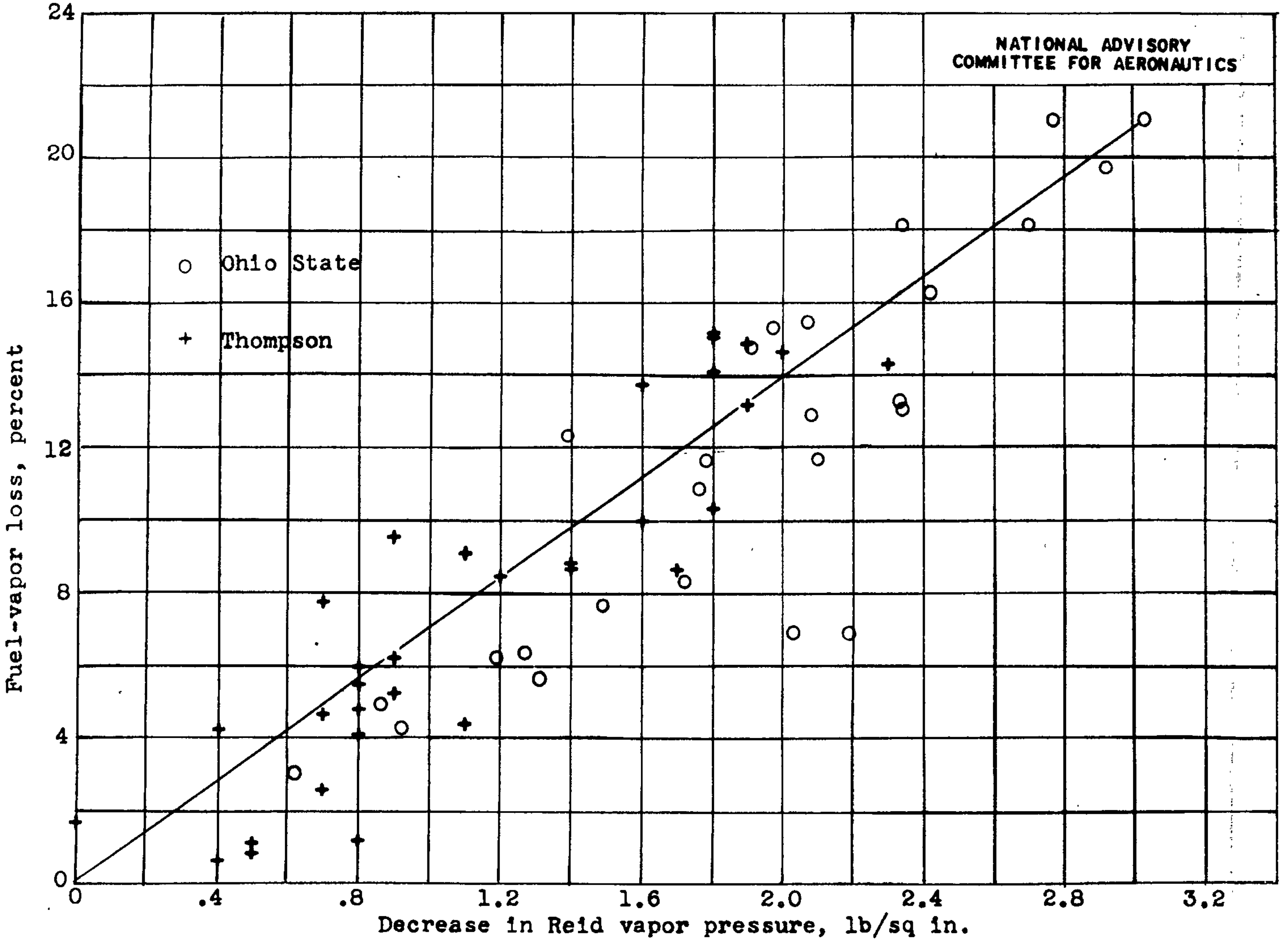



Figure 1. - The variation of fuel-vapor loss with decrease in the Reid vapor pressure of the fuel.

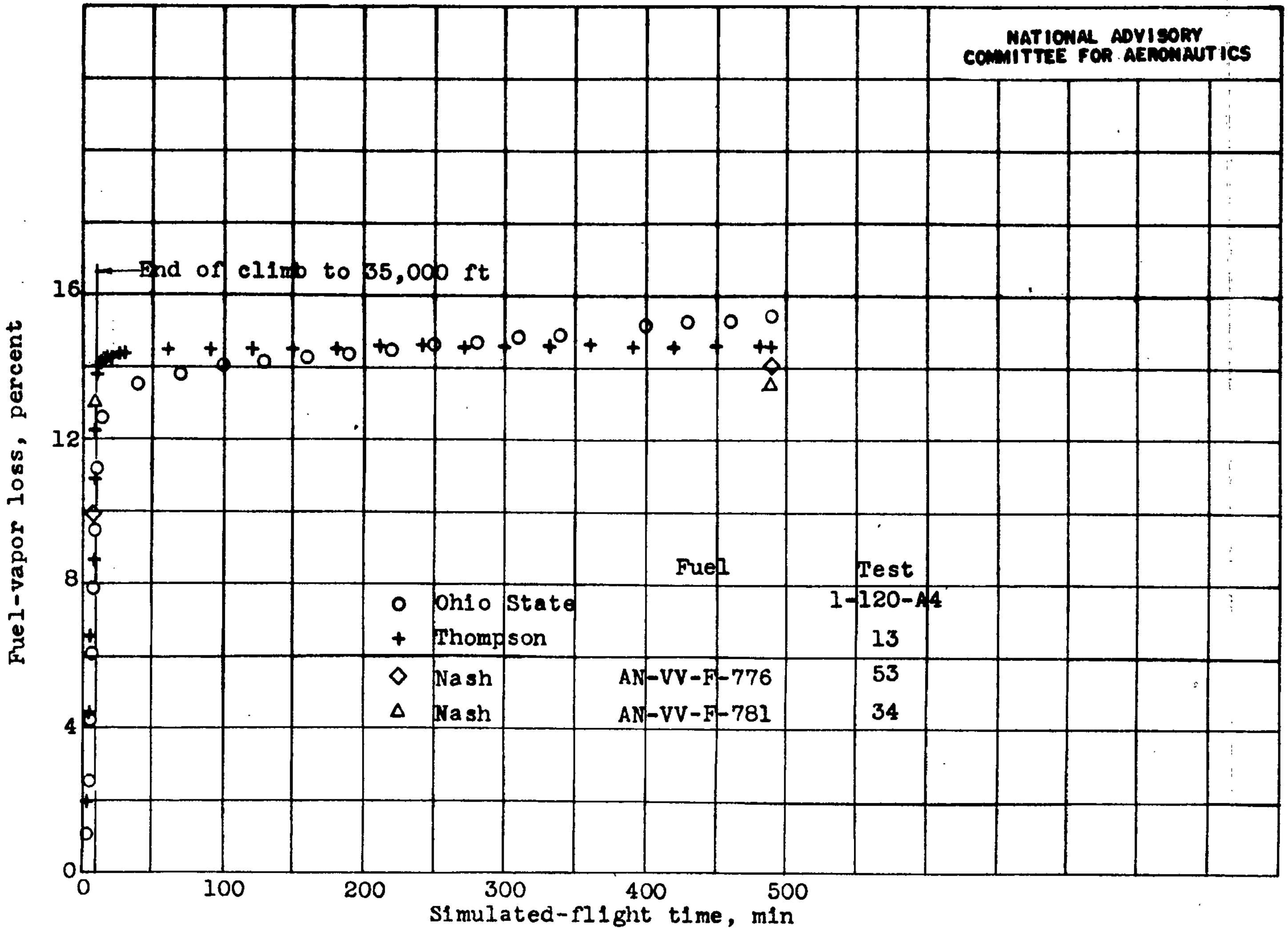
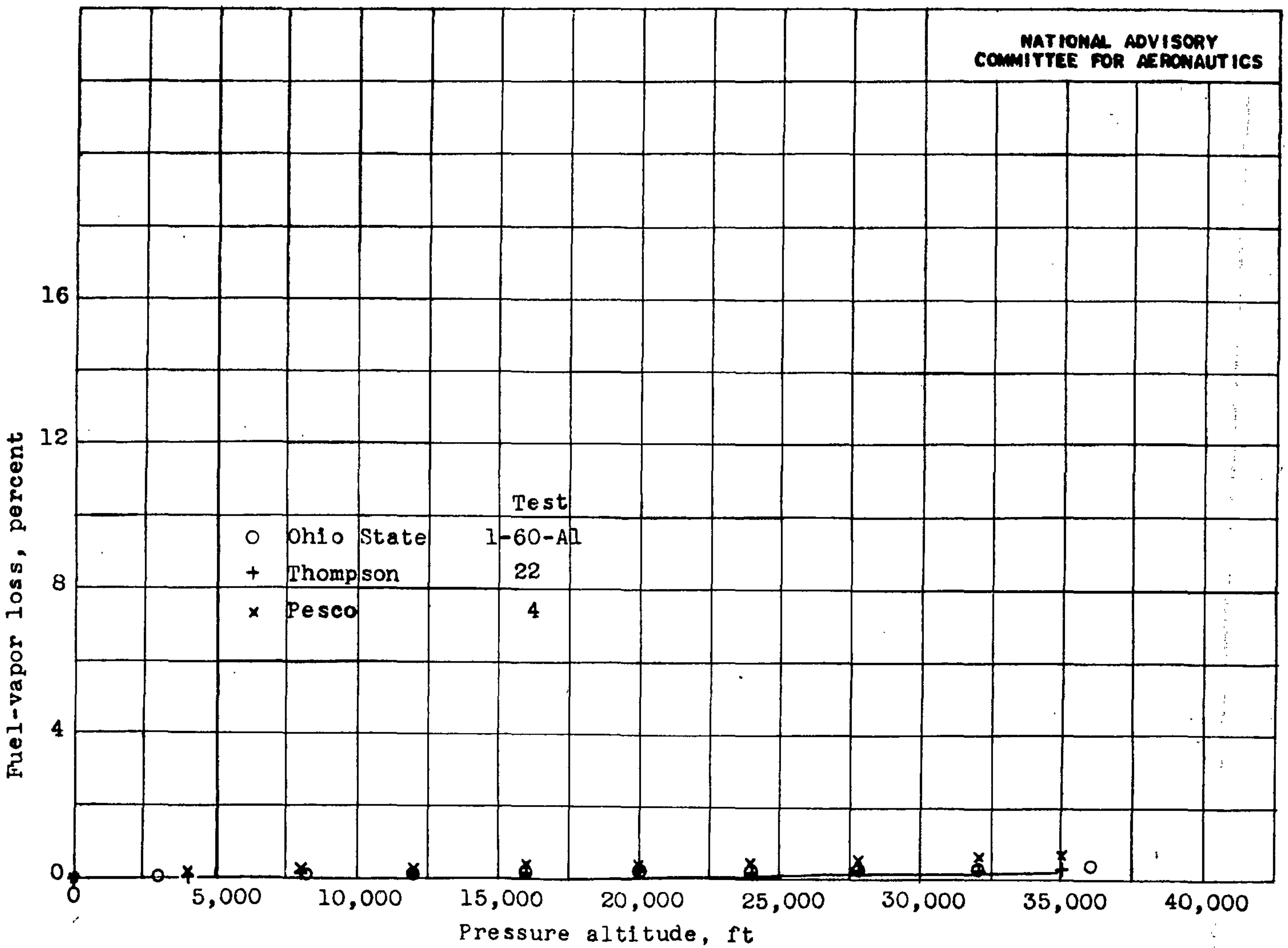
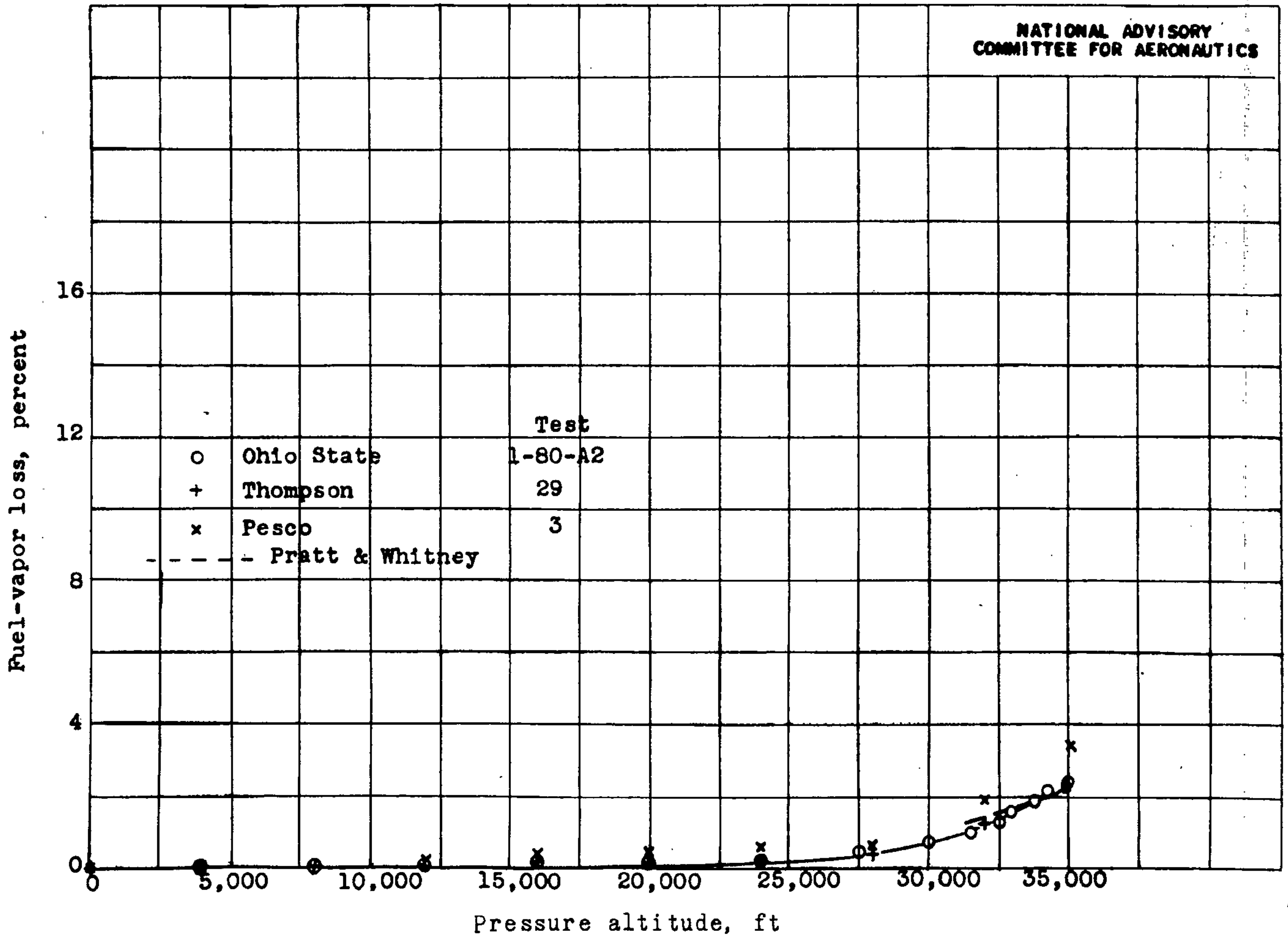



Figure 2. - Fuel-vapor loss plotted as a function of simulated-flight time. Rate of climb, 4000 feet per minute to 35,000-foot altitude, with this altitude maintained to end of test; initial fuel temperature, 120° F.



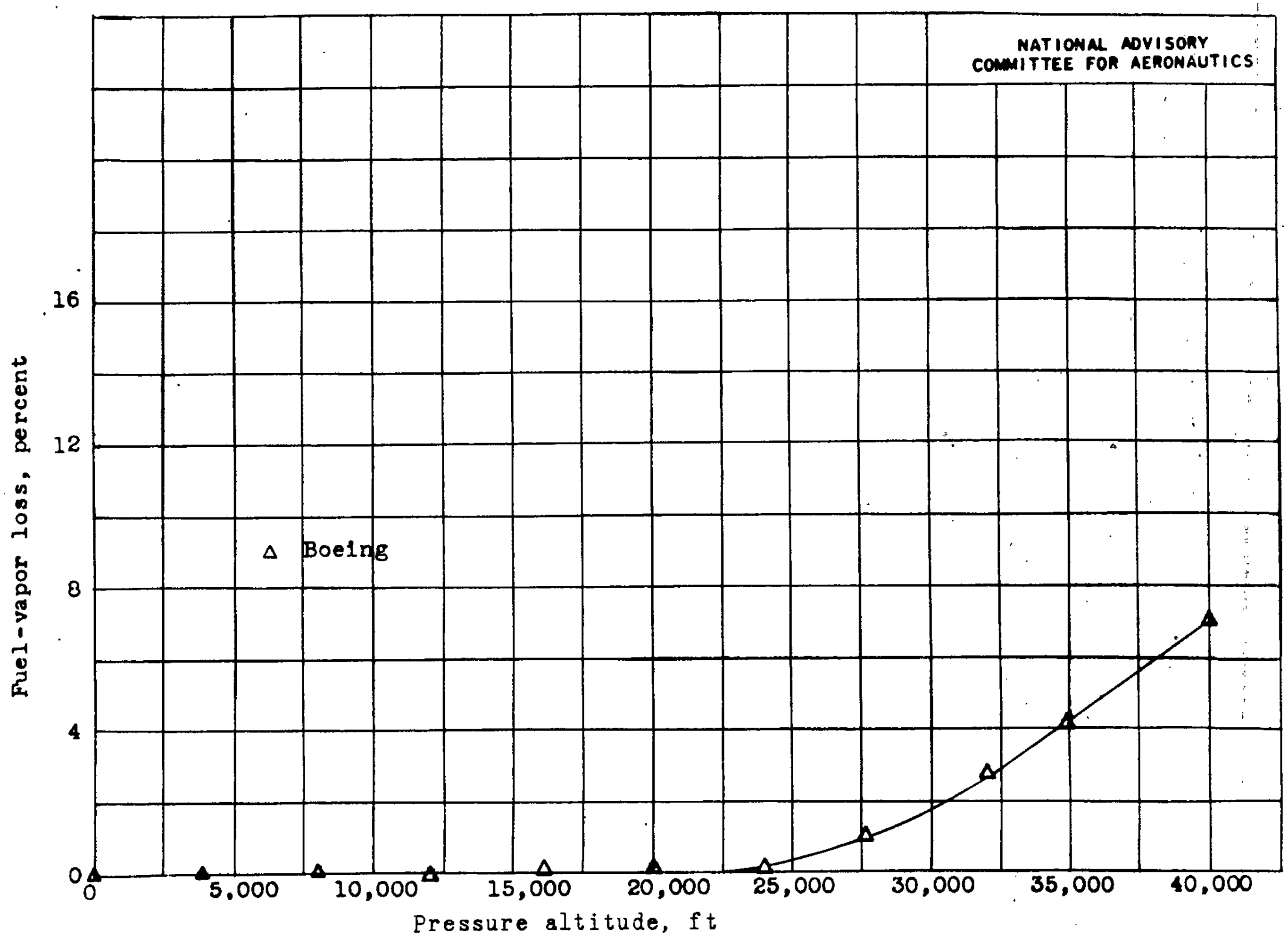

(a) Initial fuel temperature, 60° F.

Figure 3. - Fuel-vapor loss plotted as a function of pressure altitude during the climb.



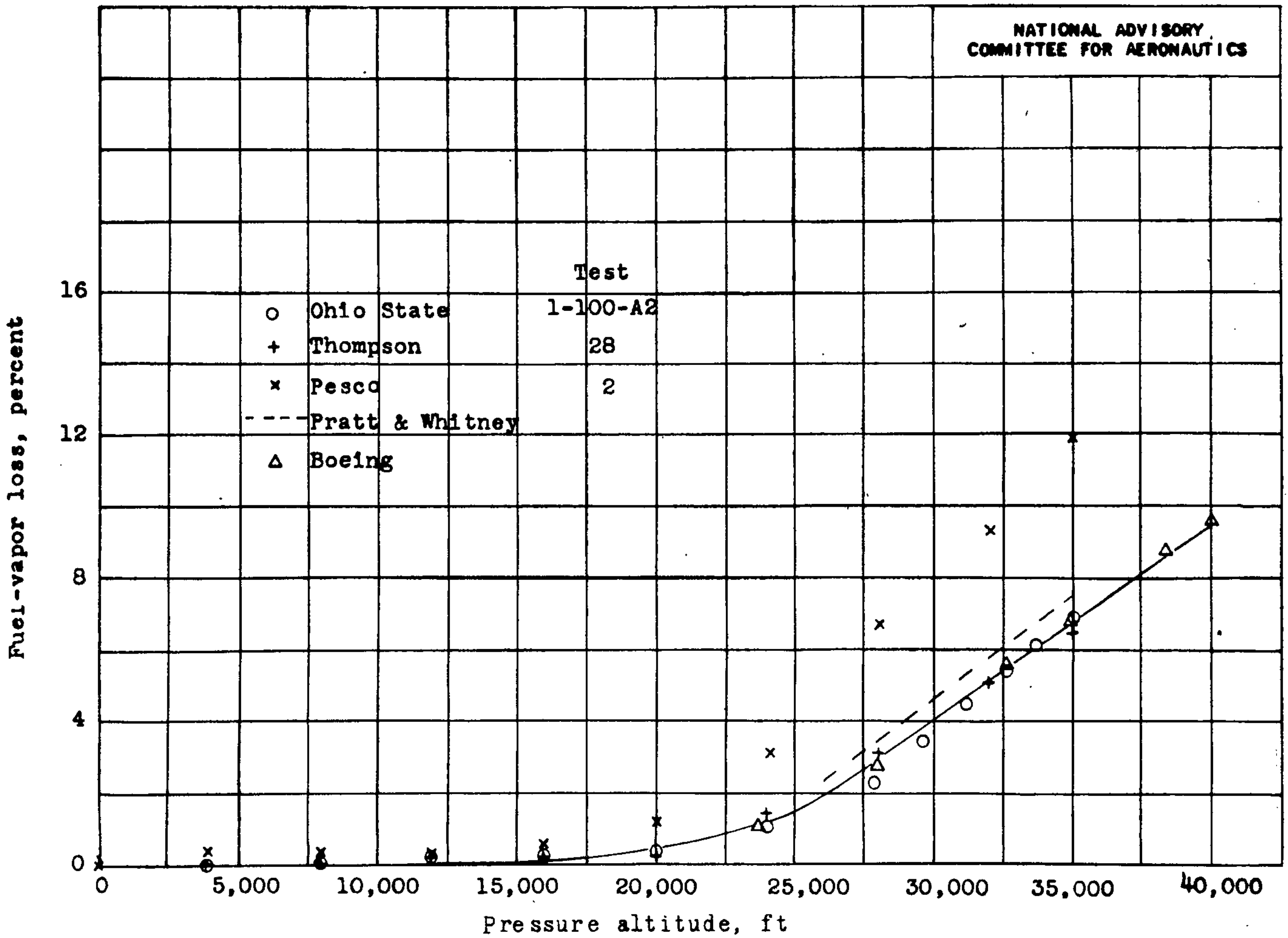

(b) Initial fuel temperature, 80° F.

Figure 3. - Continued. Fuel-vapor loss plotted as a function of pressure altitude during the climb.



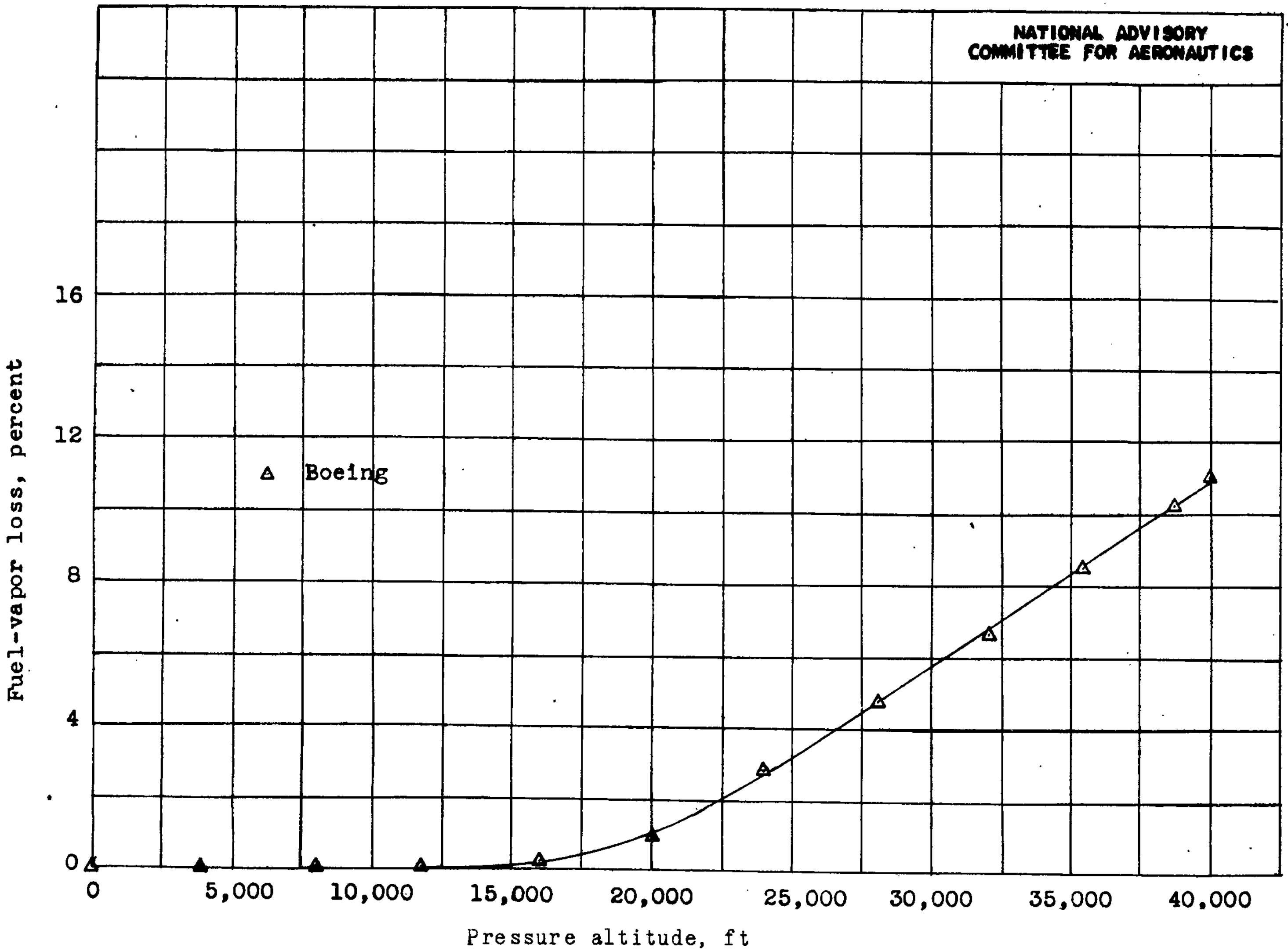

(c) Initial fuel temperature, 90° F.

Figure 3. - Continued. Fuel-vapor loss plotted as a function of pressure altitude during the climb.



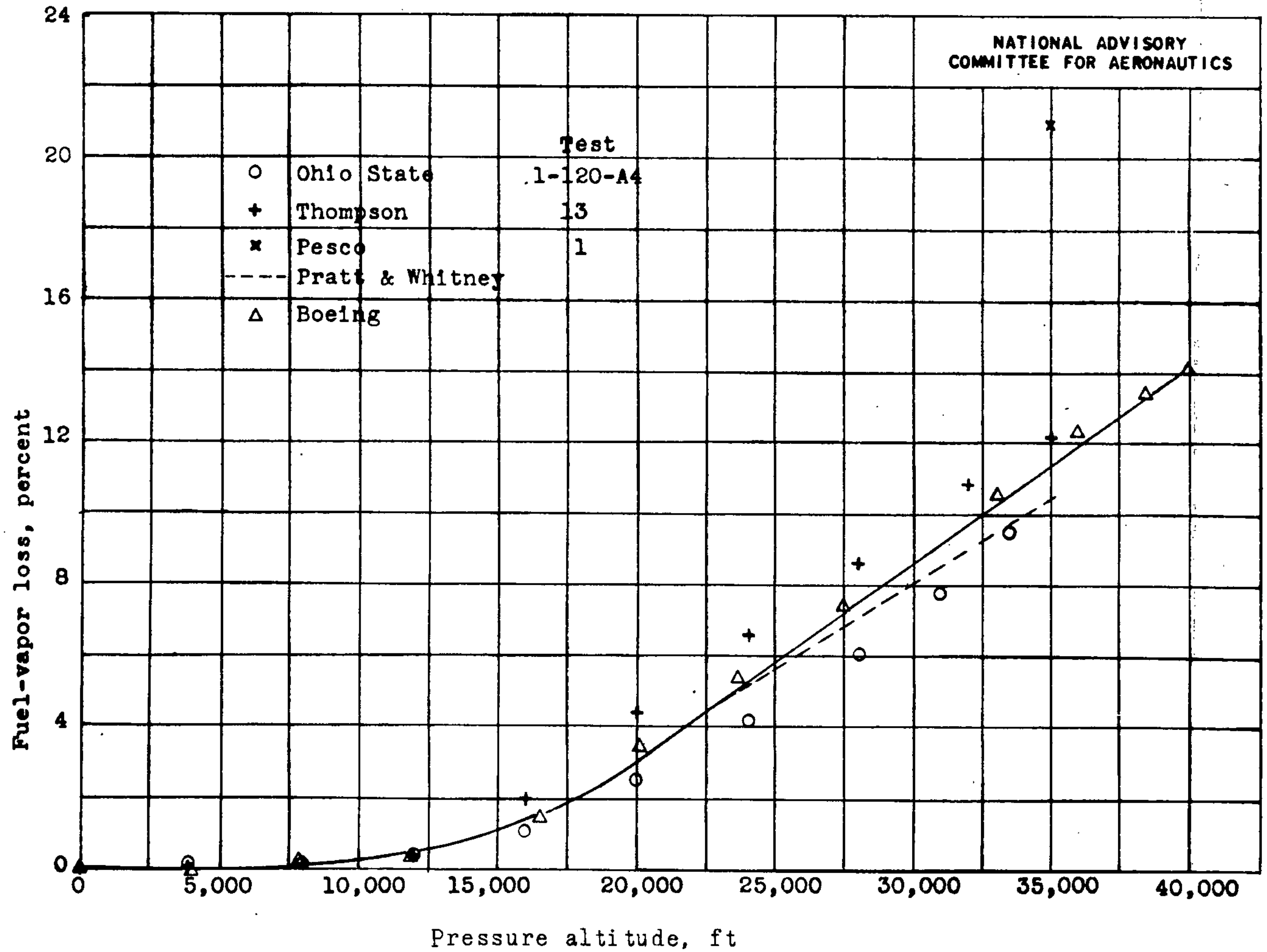

(d) Initial fuel temperature, 100° F.

Figure 3. - Continued. Fuel-vapor loss plotted as a function of pressure altitude during the climb.




(e) Initial fuel temperature, 110° F.

Figure 3. - Continued. Fuel-vapor loss plotted as a function of pressure altitude during the climb.




(f) Initial fuel temperature, 120° F.

Figure 3. - Concluded. Fuel-vapor loss plotted as a function of pressure altitude during the climb.

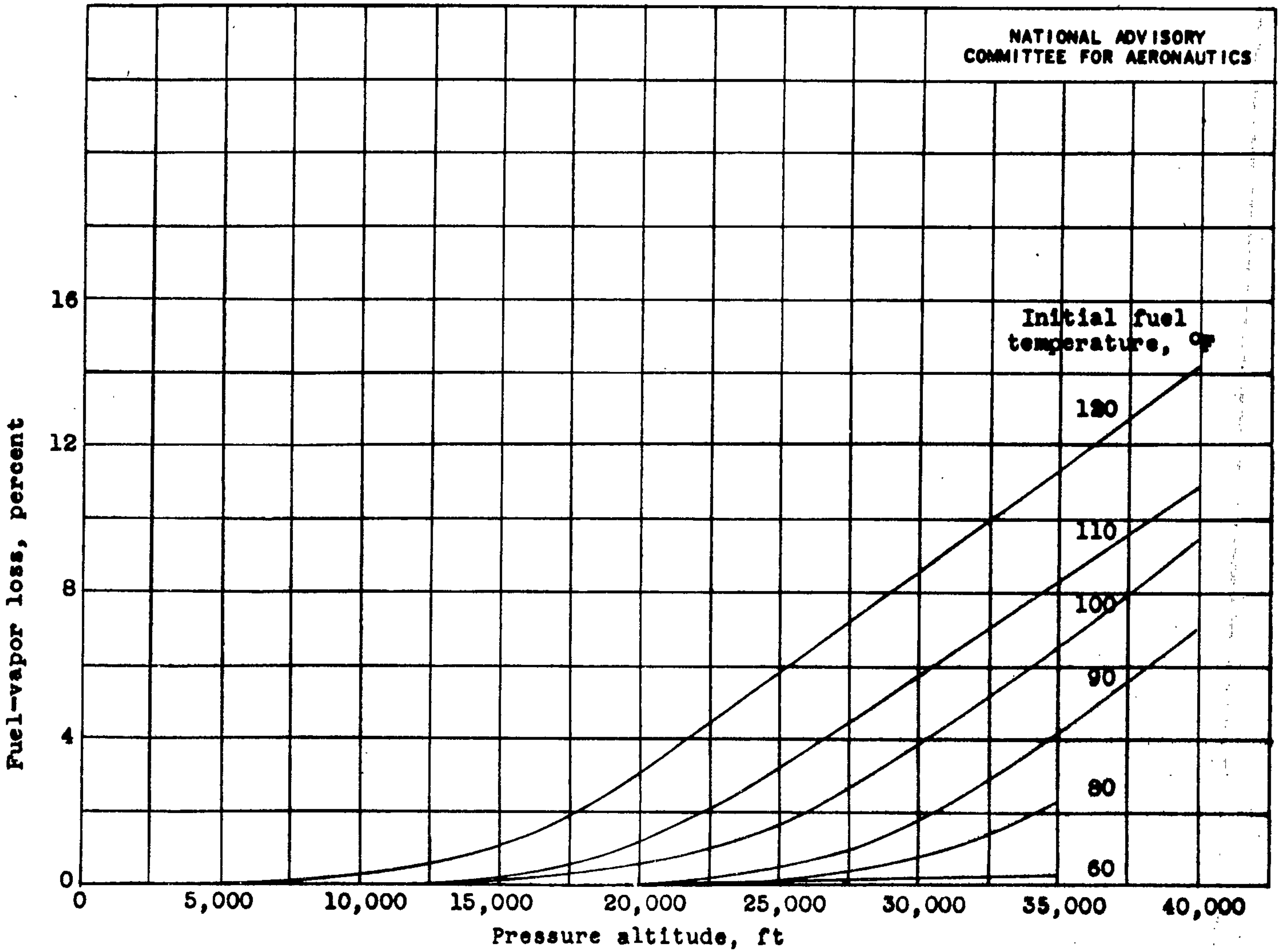



Figure 4. - Fuel-vapor loss plotted as a function of pressure altitude during the climb for several initial fuel temperatures. (Replot of average curves from fig. 3.)

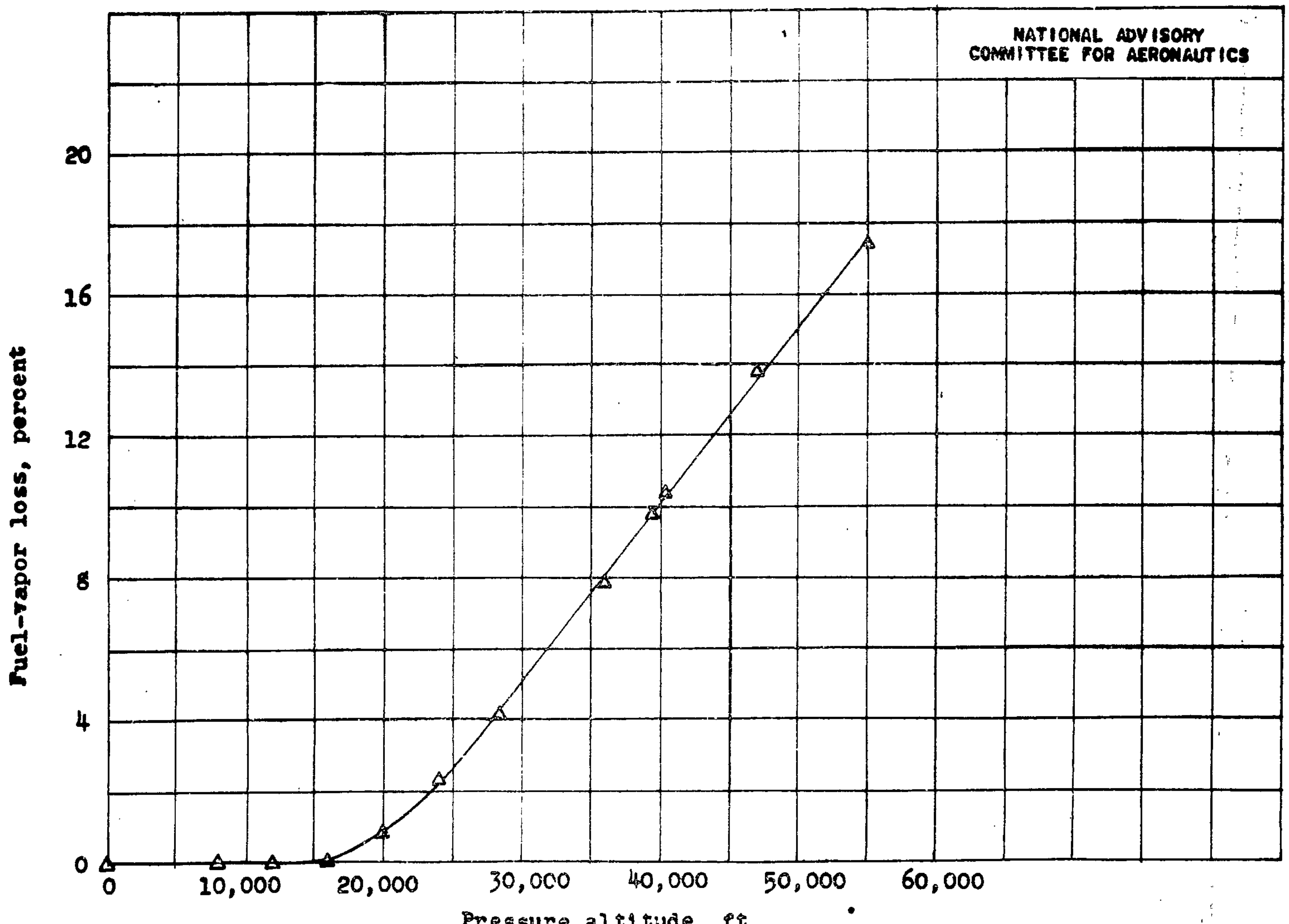



Figure 5. - Fuel-vapor loss plotted as a function of pressure altitude during the climb. Initial fuel temperature, 110° F.

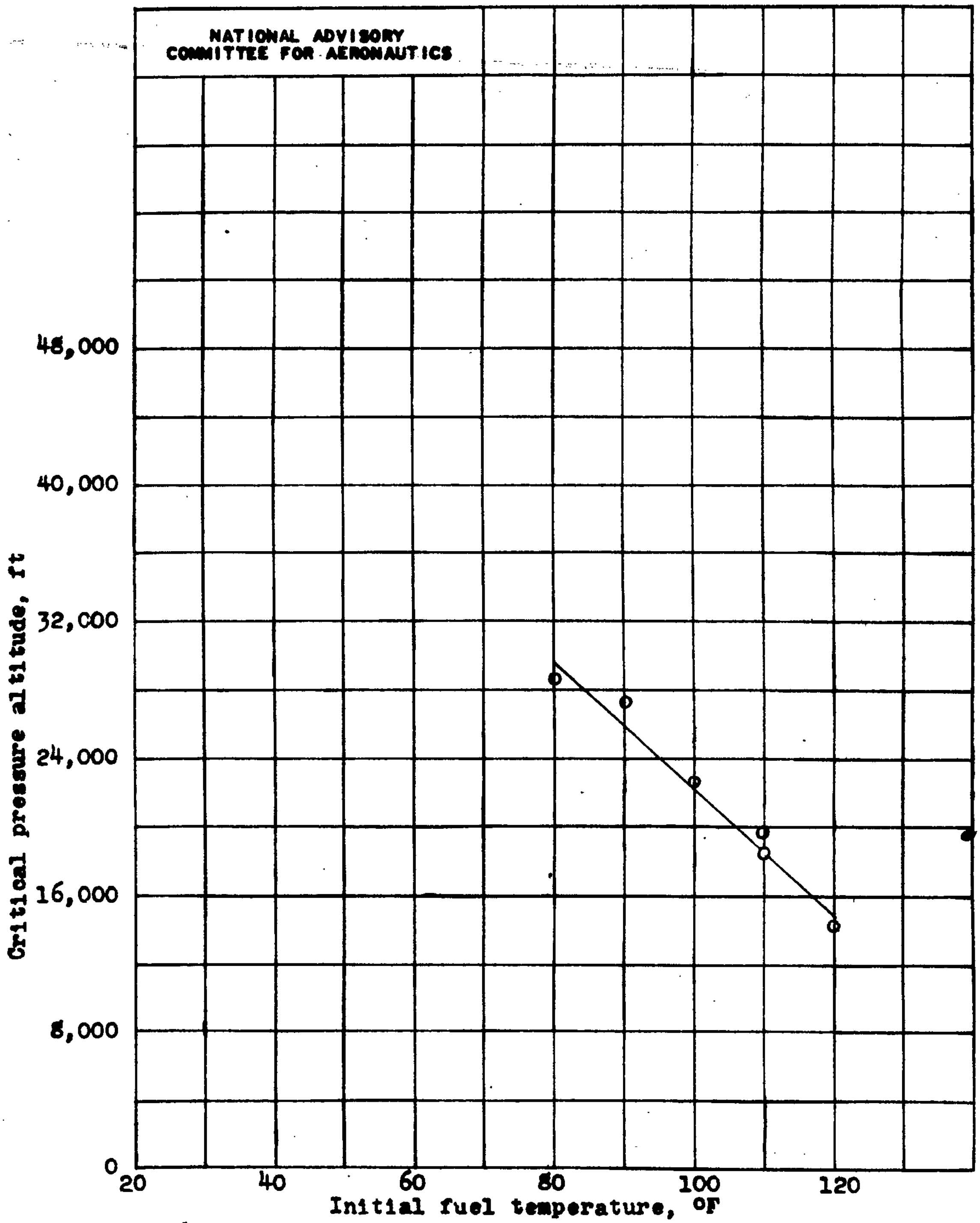
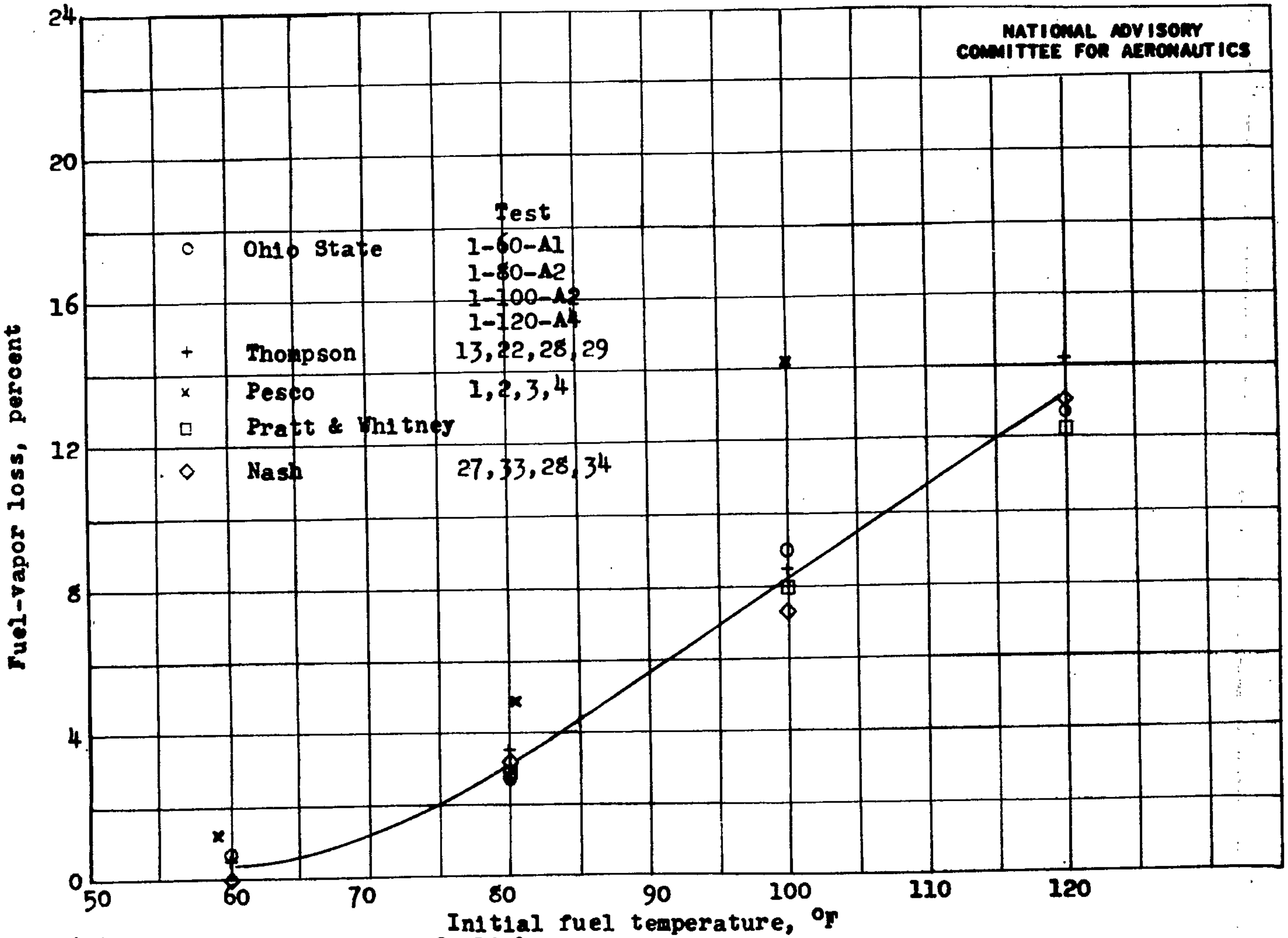
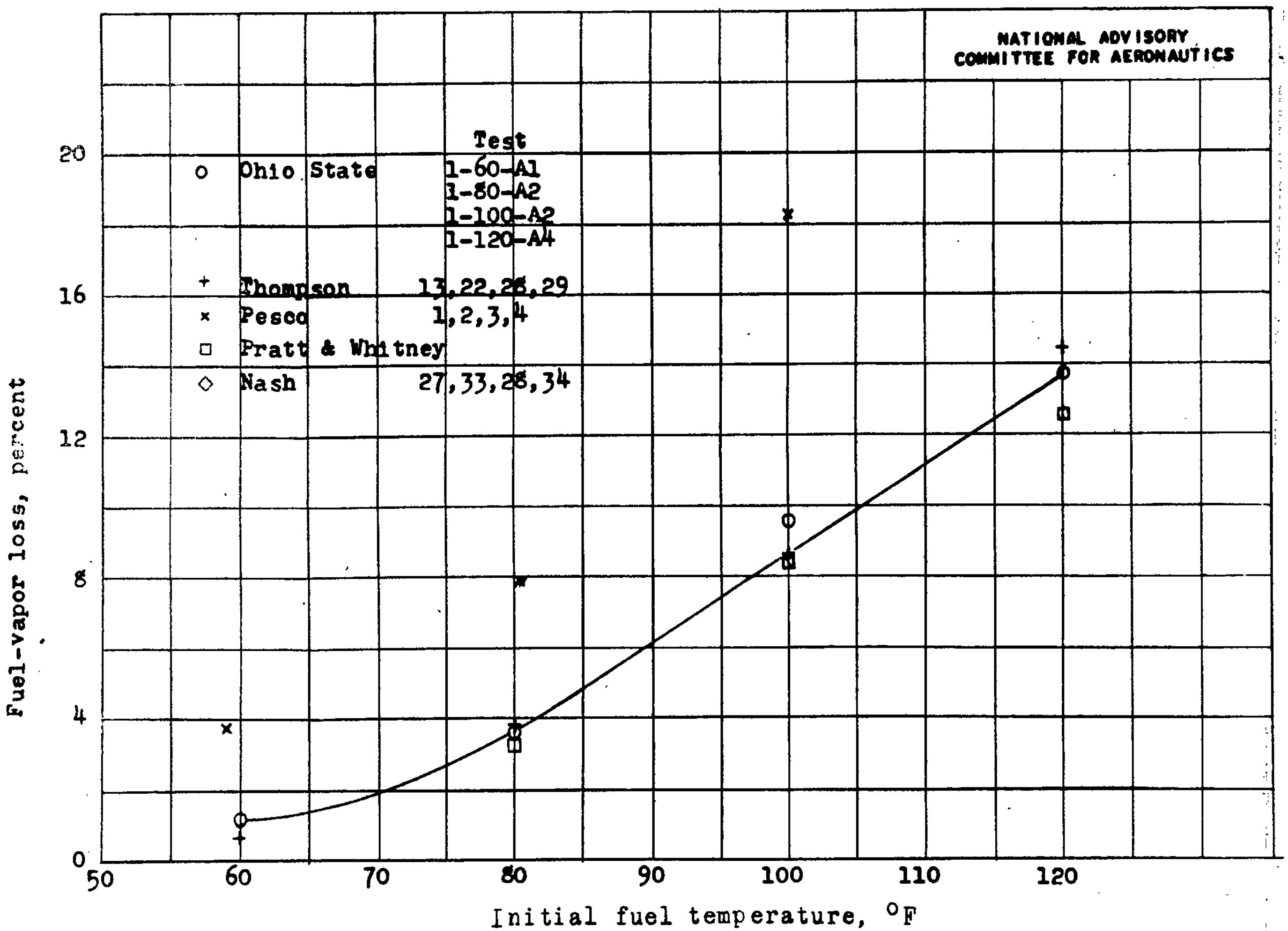



Figure 6. - Critical pressure altitude plotted as a function of initial fuel temperature. (Data derived from figs. 4 and 5.)



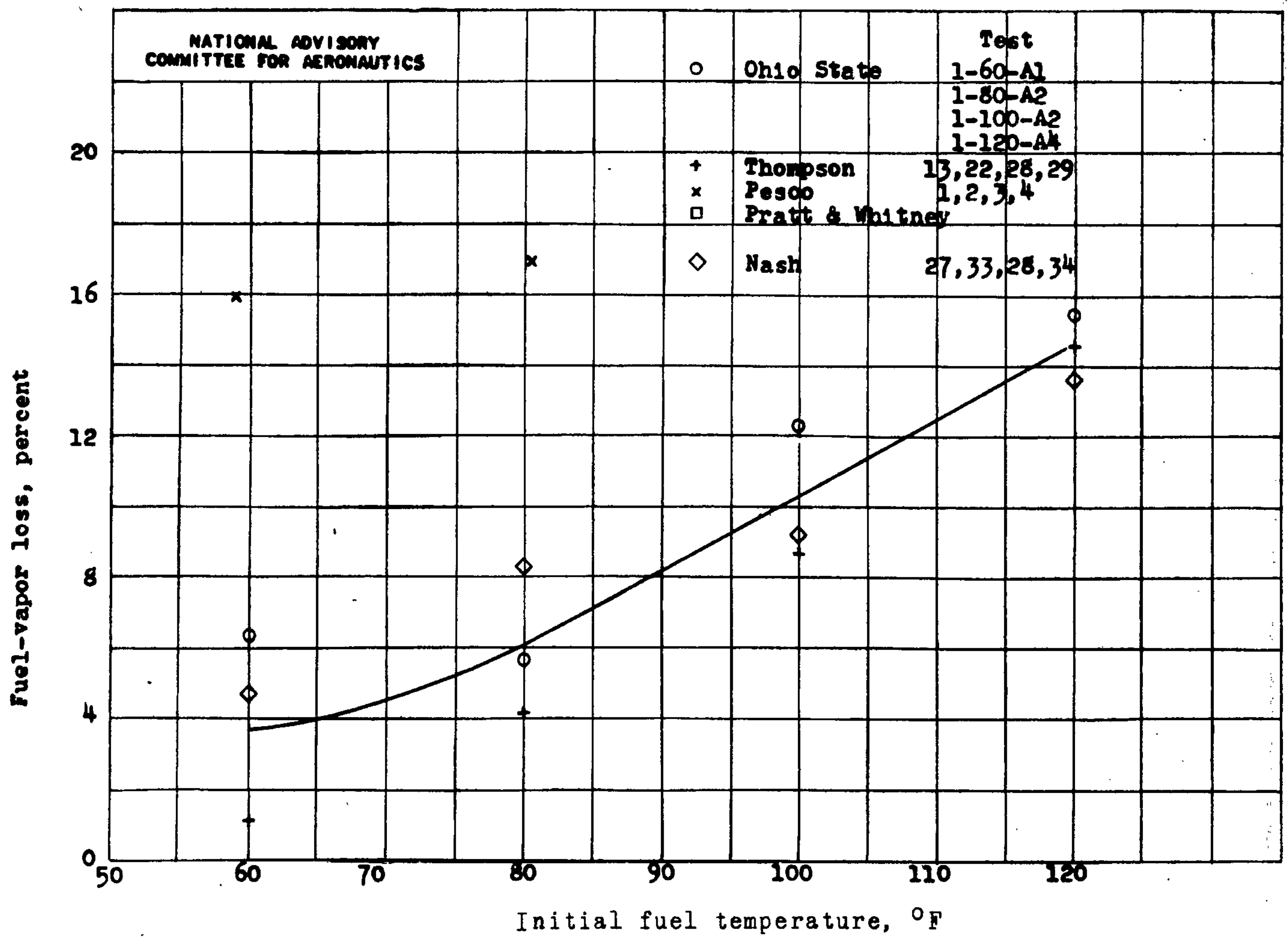

(a) 10 minutes after end of climb.

Figure 7. - Fuel-vapor loss plotted as a function of initial fuel temperature with fuel unagitated. Climb to 35,000 feet with this altitude maintained to the end of the flight. (Data points obtained by interpolating tabular data where necessary.)




(b) 1 hour after end of climb.

Figure 7. - Continued. Fuel-vapor loss plotted as a function of initial fuel temperature with fuel unagitated. Climb to 35,000 feet with this altitude maintained to the end of the flight. (Data points obtained by interpolating tabular data where necessary.)




(c) 8 hours after end of climb.

Figure 7. - Concluded. Fuel-vapor loss plotted as a function of initial fuel temperature with fuel unagitated. Climb to 35,000 feet with this altitude maintained to the end of the flight. (Data points obtained by interpolating tabular data where necessary.)

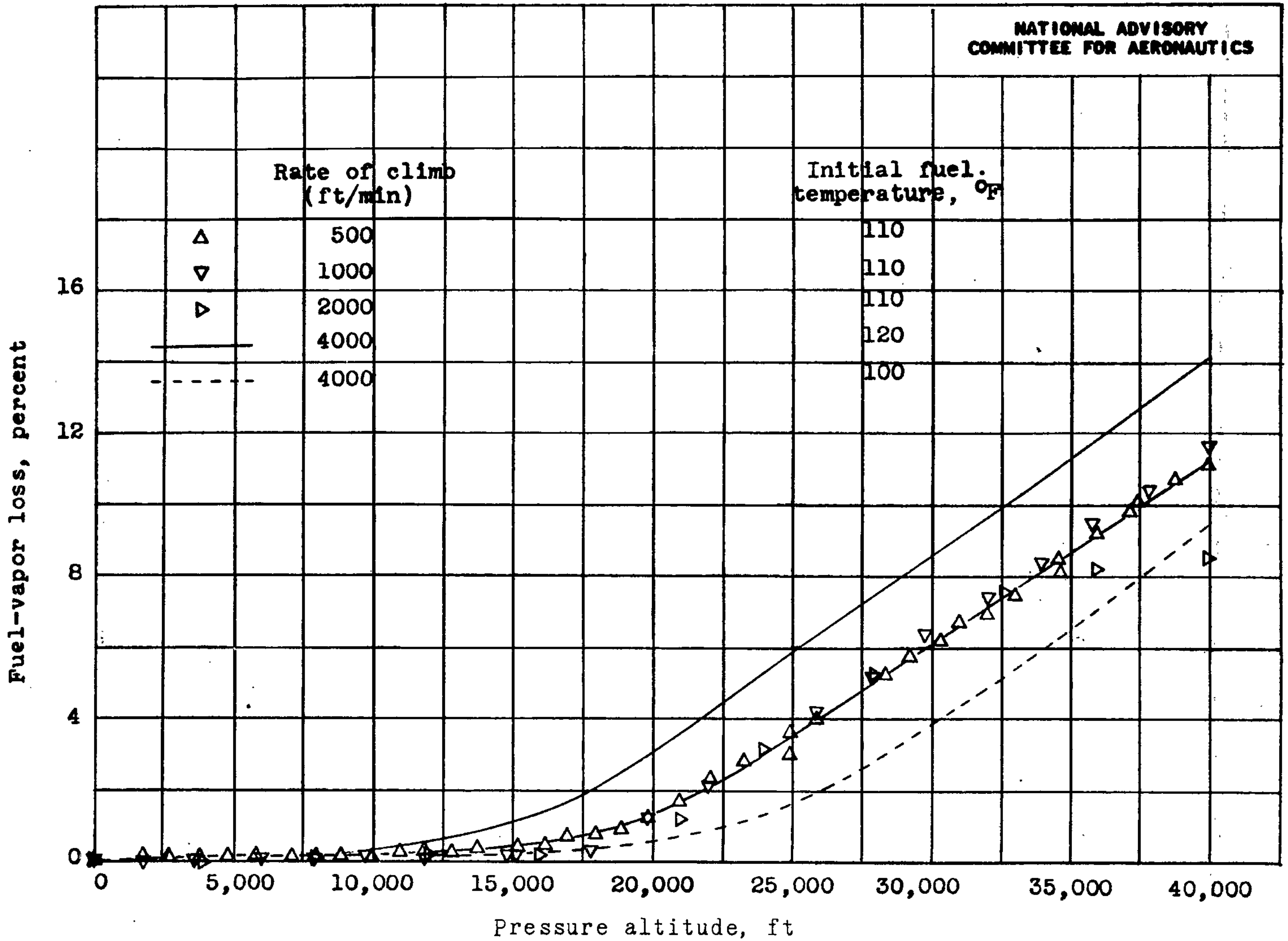
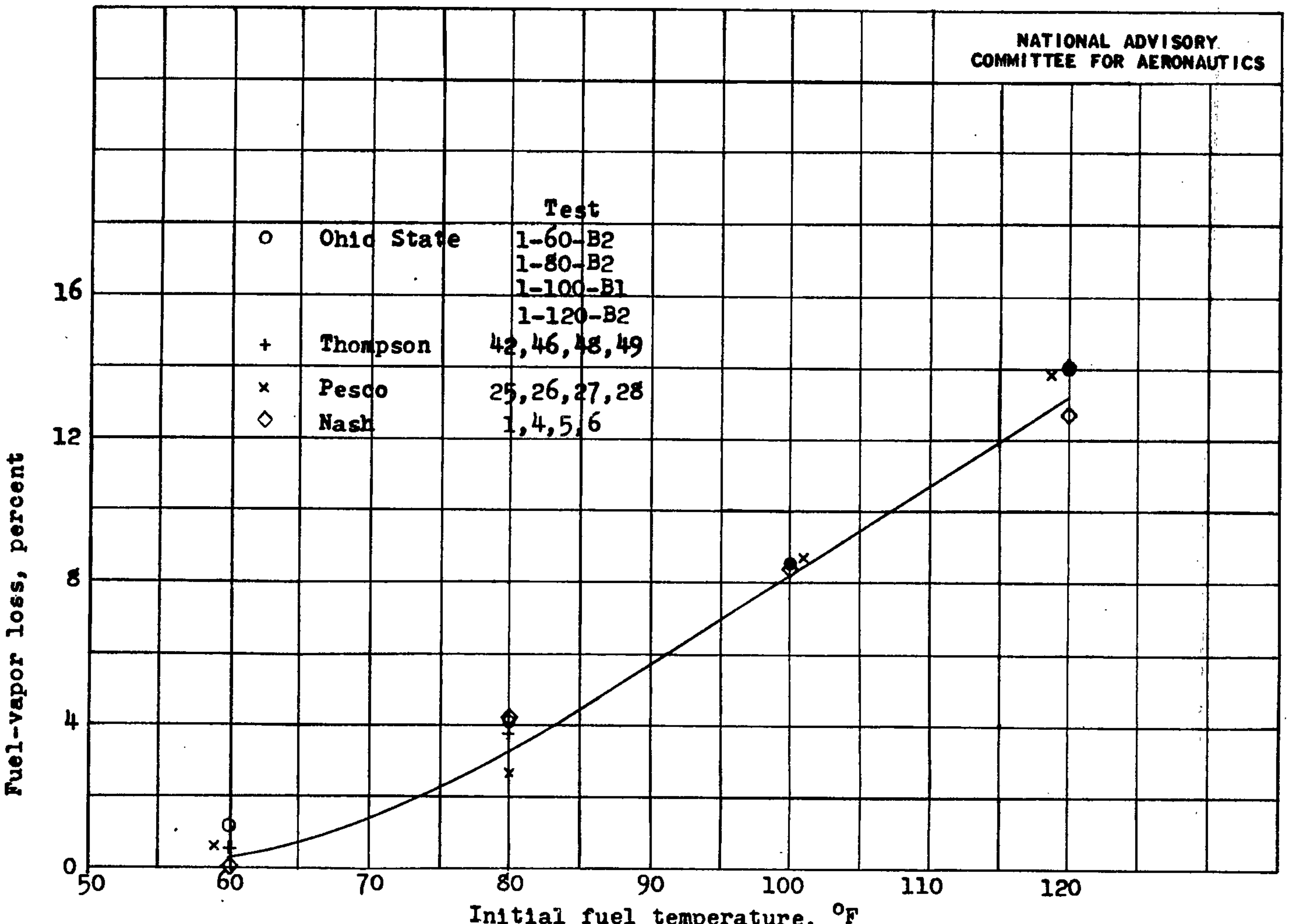
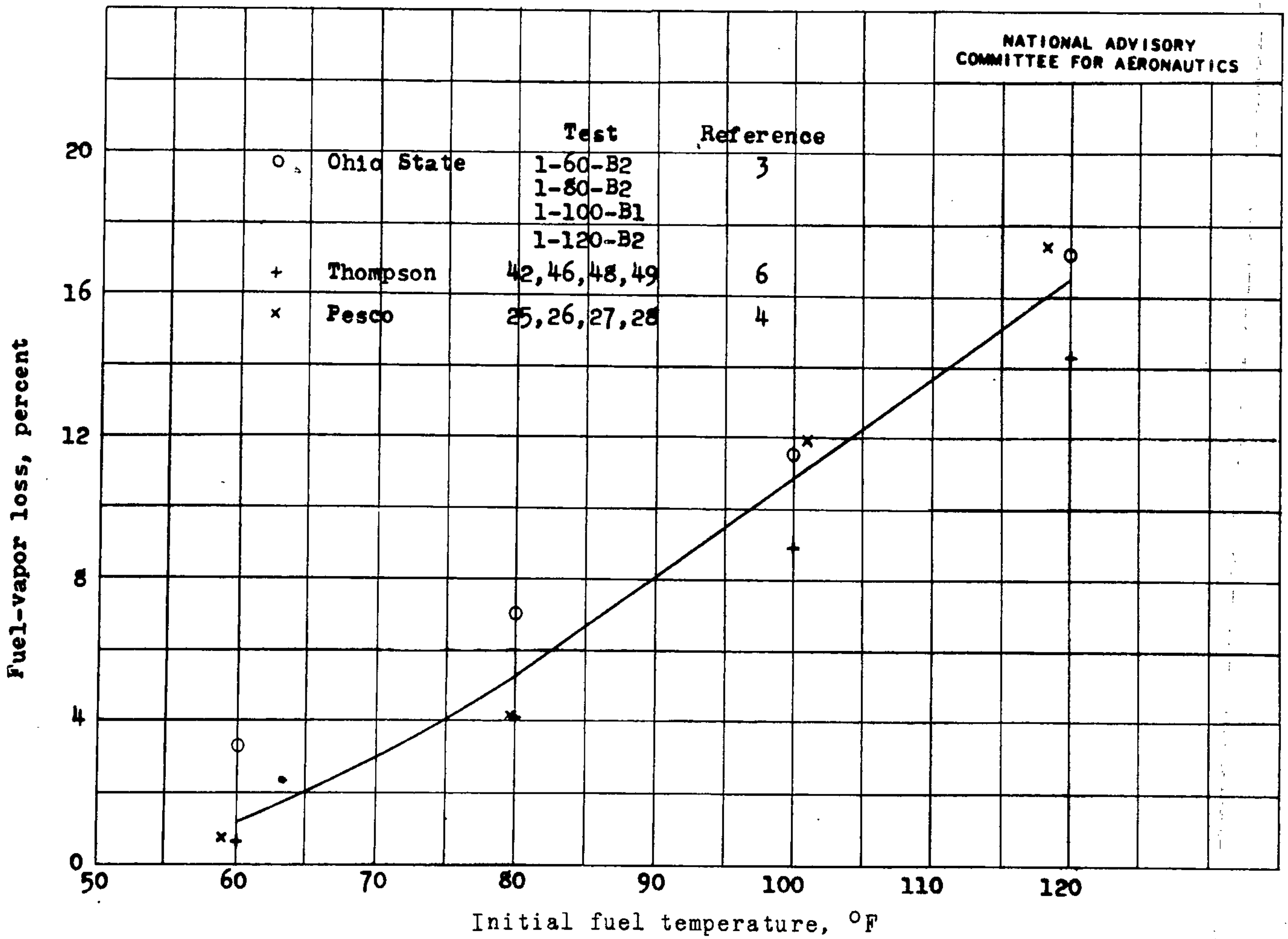



Figure 8. - Effect of rate of climb on fuel-vapor loss during the climb period of a simulated flight. (Data from Boeing tests.)



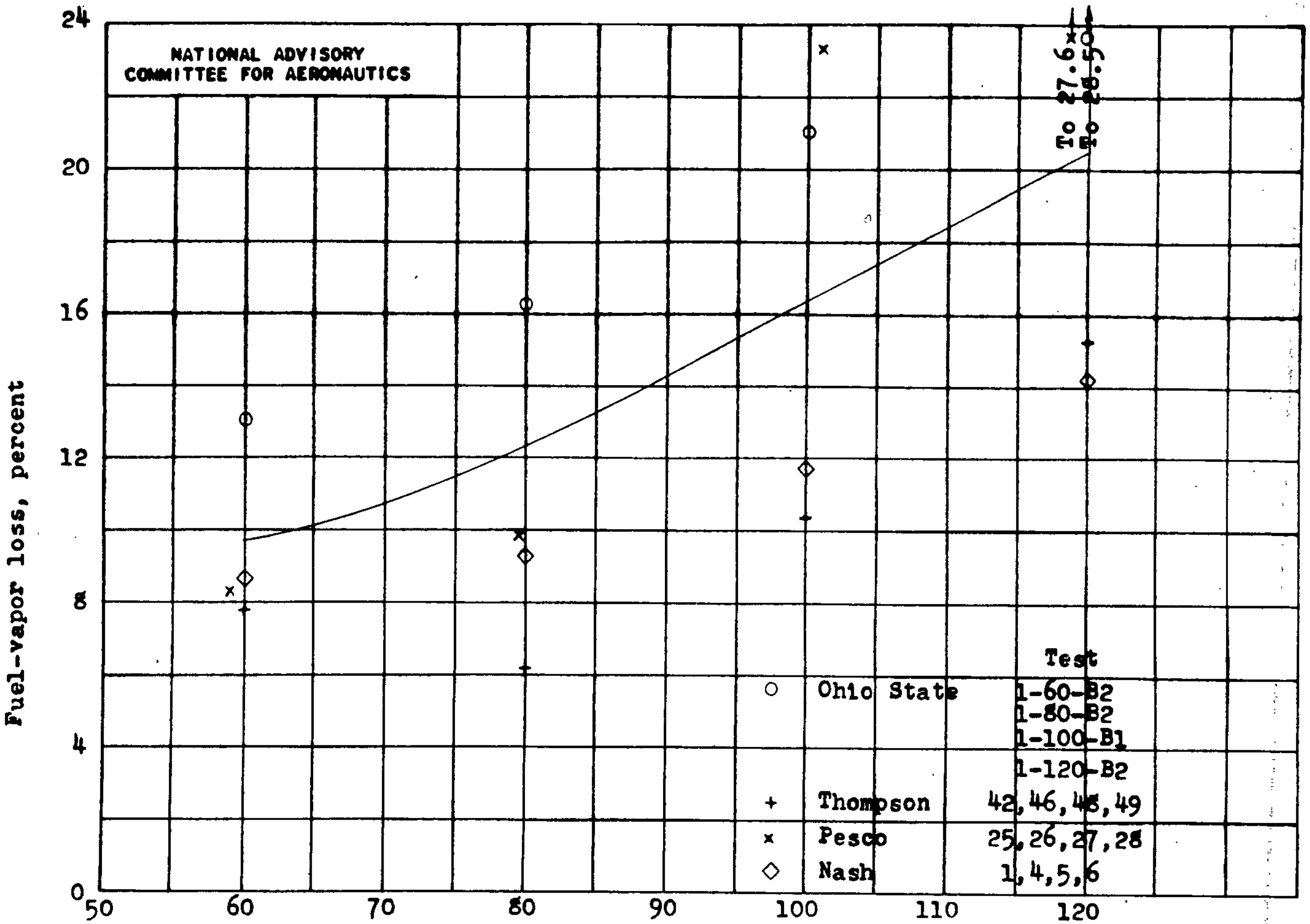

(a) 10 minutes after end of climb.

Figure 9. - Fuel-vapor loss as a function of initial fuel temperature with fuel agitated by booster pump. Climb to 35,000 feet with this altitude maintained to end of test. (Data points obtained by interpolating tabular data where necessary.)




(b) 1 hour after end of climb.

Figure 9. - Continued. Fuel-vapor loss as a function of initial fuel temperature with fuel agitated by booster pump. Climb to 35,000 feet with this altitude maintained to end of test. (Data points obtained by interpolating tabular data where necessary.)




(c) 8 hours after end of climb.

Figure 9. - Concluded. Fuel-vapor loss as a function of initial fuel temperature with fuel agitated by booster pump. Climb to 35,000 feet with this altitude maintained to end of test. (Data points obtained by interpolating tabular data where necessary.)

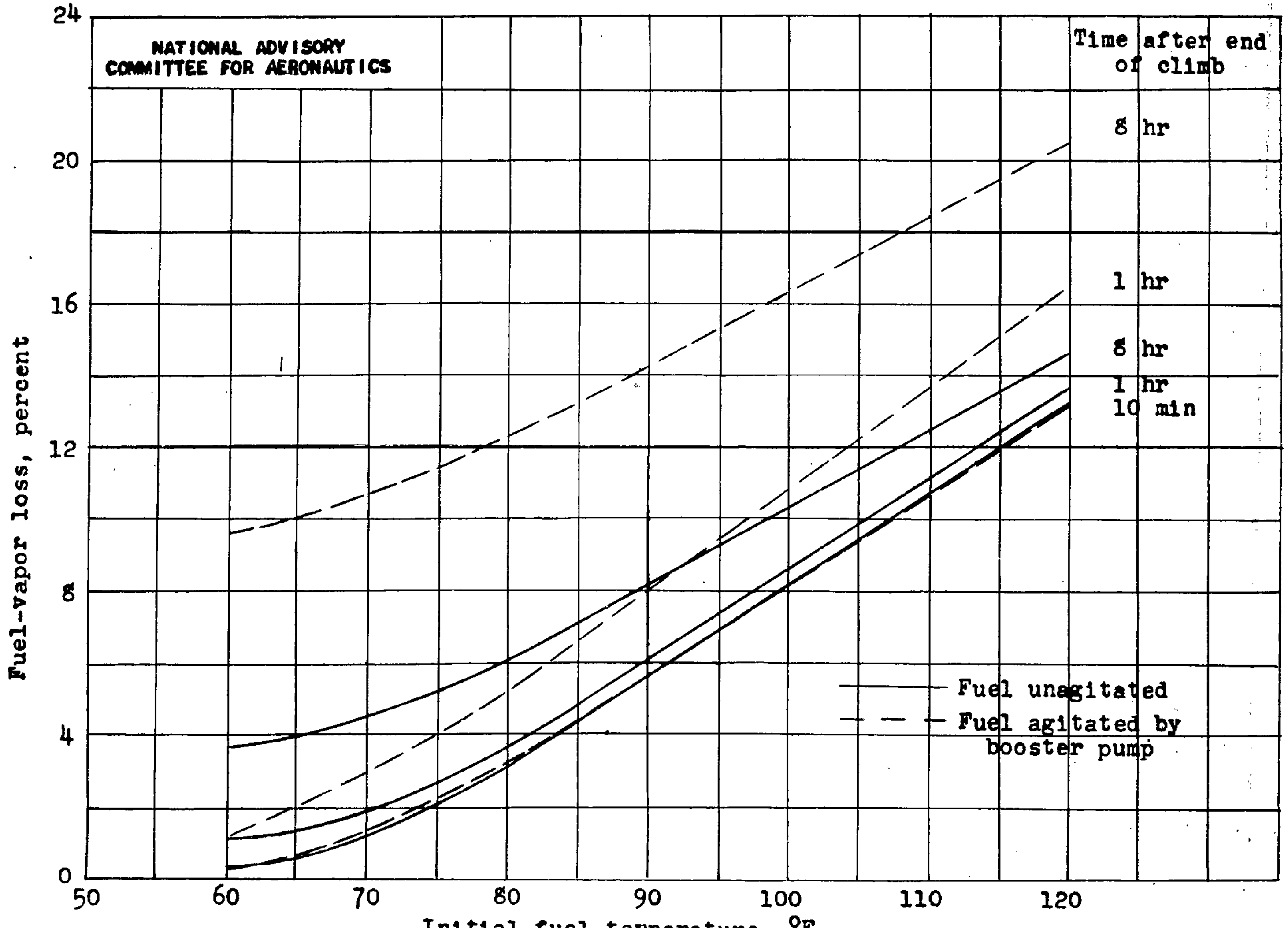



Figure 10. - The effect of agitation on fuel-vapor loss during simulated flight. Climb to 35,000 feet with this altitude maintained to end of test. (Replot of average curves from figs. 7 and 9.)

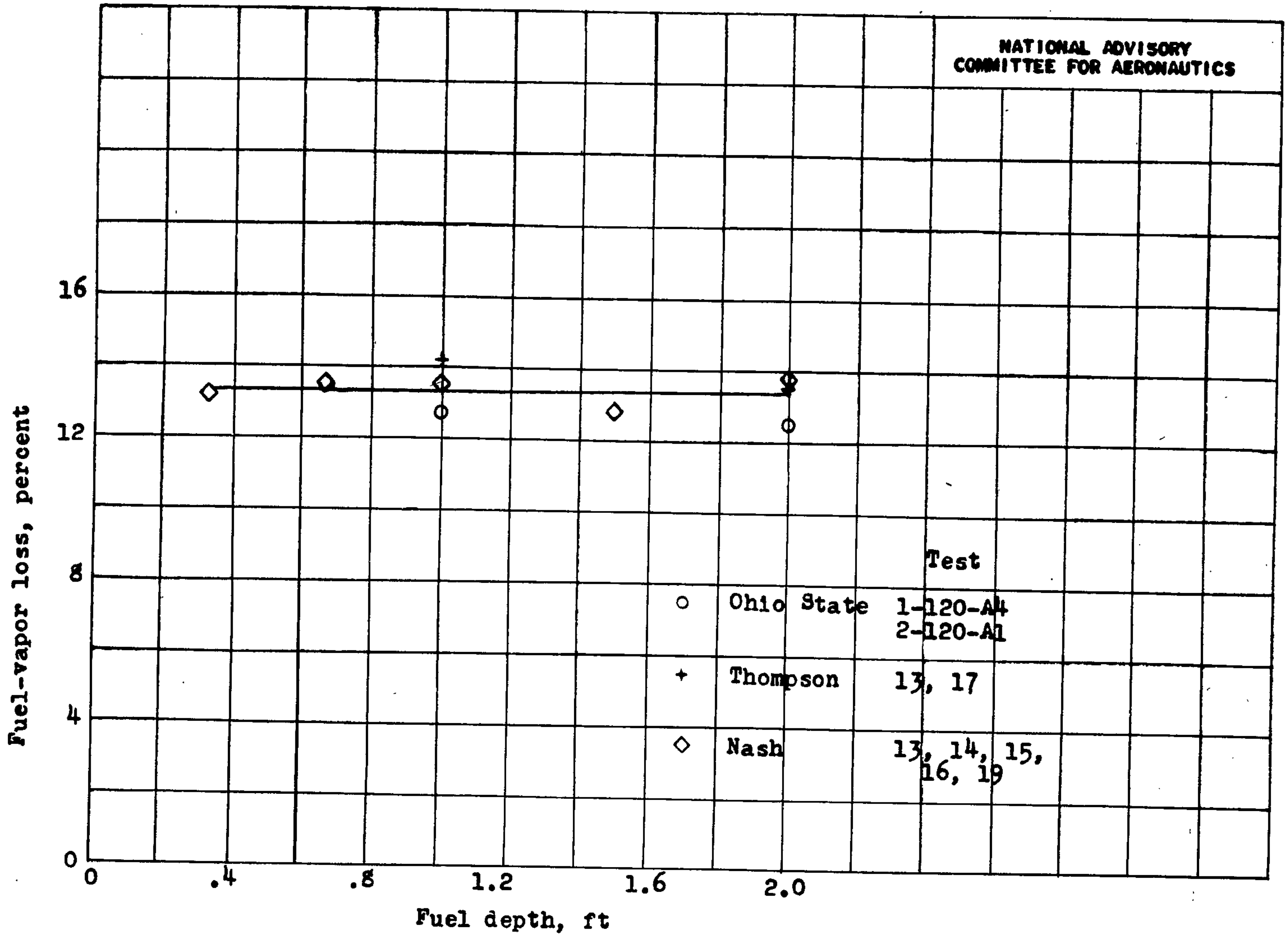
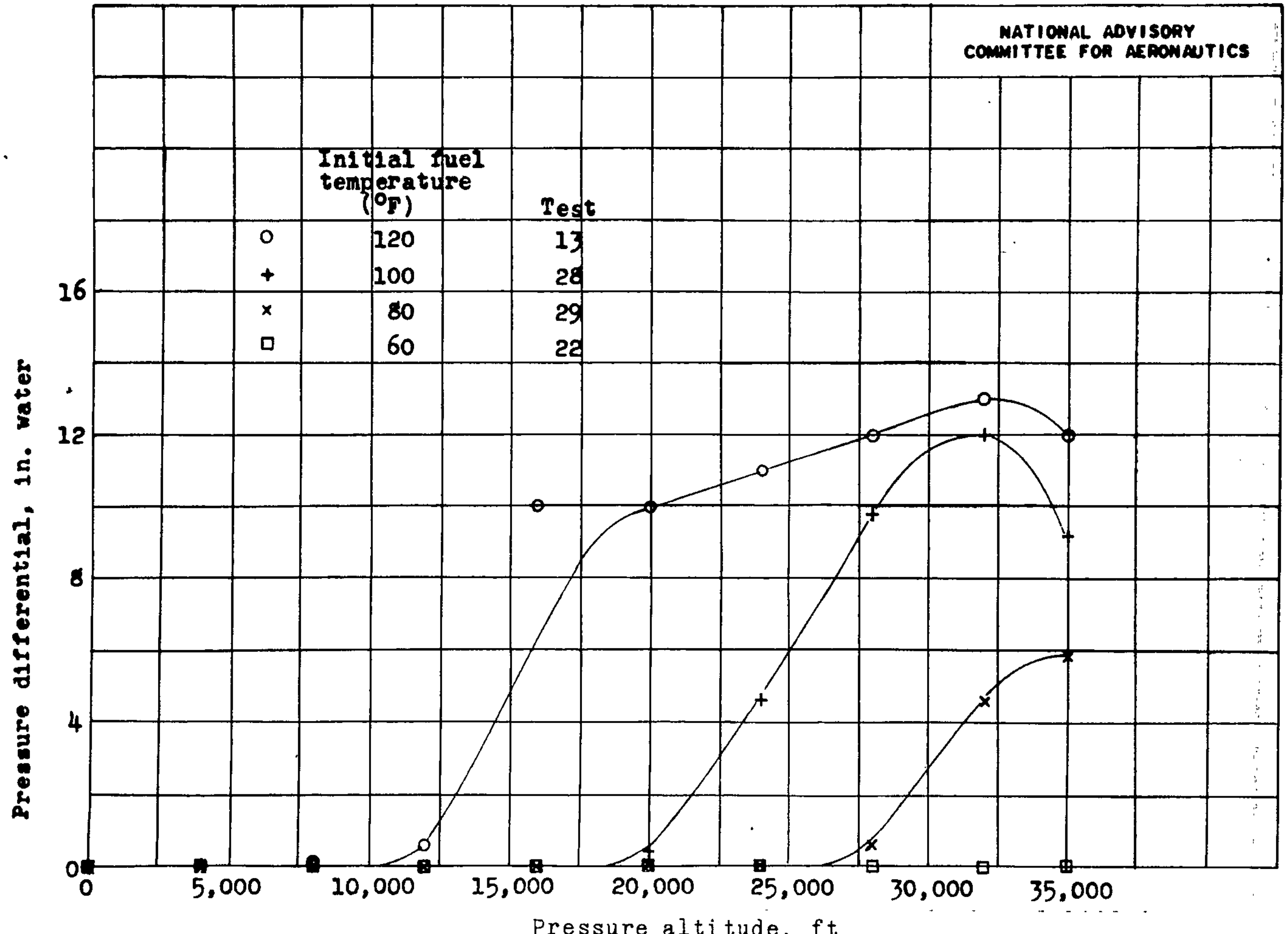



Figure 11. - Variation of fuel-vapor loss with fuel depth during simulated flight. Climb to 35,000 feet with this altitude maintained for 10 minutes; initial fuel temperature, 120° F.




(b) Thompson data.

Figure 12. - Concluded. Vent-line pressure differential plotted as a function of pressure altitude for several initial fuel temperatures. Rate of climb, 4000 feet per minute.

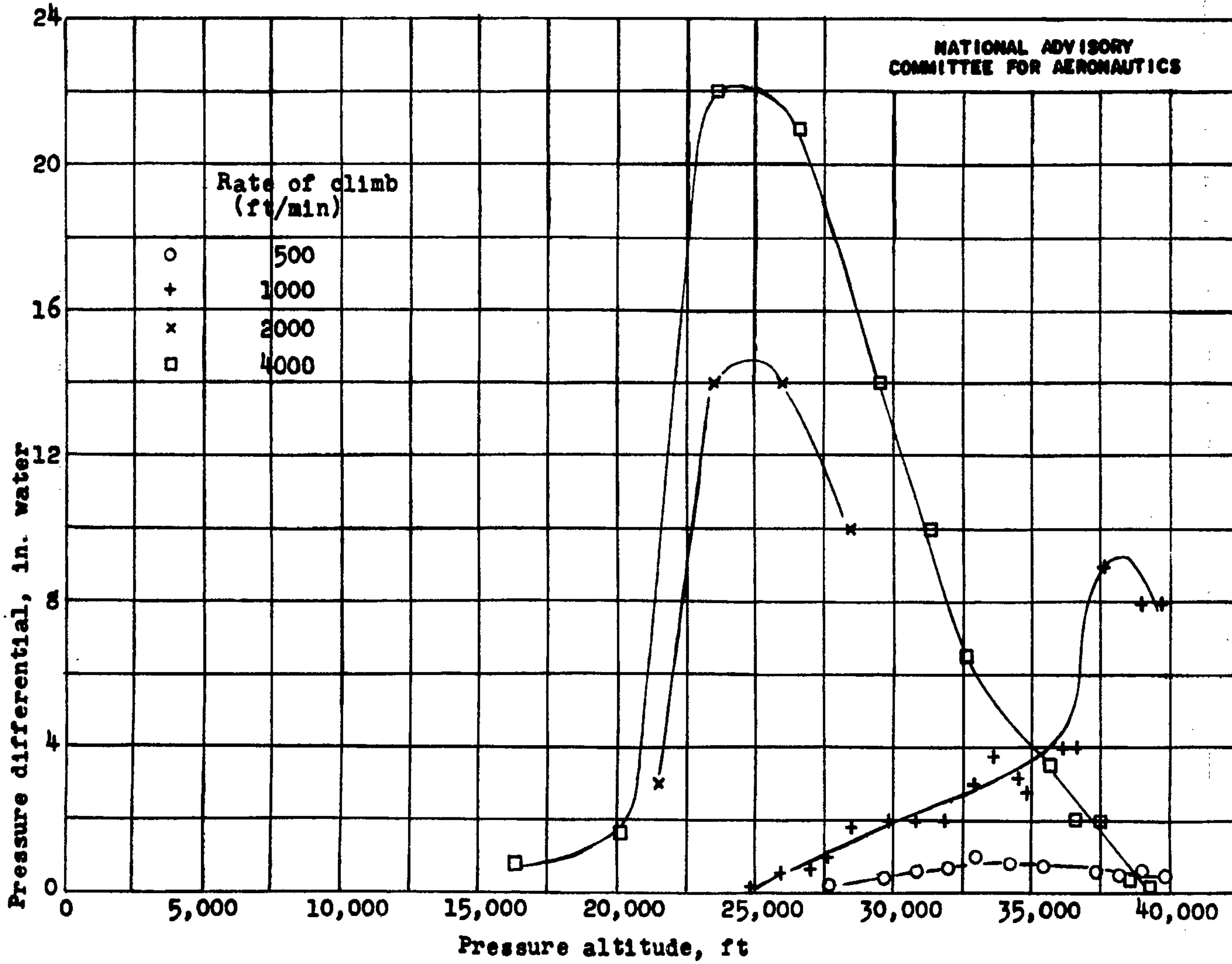



Figure 13. - Vent-line pressure differential plotted as a function of pressure altitude during simulated flights at several rates of climb obtained by Boeing. Initial fuel temperature, 110° F.